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COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

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USER'S GUIDE: PILE GROUP ANALYSIS (CPGA) COMPUTER PROGRAM

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and Substructures

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A computer program for basic pile group analysis, CPGA, was developed through the Computer-Aided Structural Engineering (CASE) Project by the Task Group on Pile Structures and Substructures. It is intended to be a simple program for pile group analysis to eliminate many of the inaccuracies inherent in hand analysis methods. The program assumes the pile cap to be rigid and the piles to be linearly elastic. Soil resistance to pile movement may be included. This technical report includes material as a user's manual in Part I and theoretical and background material in Part II. Keywords:

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Contributing Authors: Messrs. Bigham, James, Brown, Roger, Chun, Richard, Demsky, Edward, Hoell, Roger, Jones, Wayne, Napolitano, Phil, Ruckstuhl, Charles, and Strom, Ralph

PROGRAM INFORMATION

Description of Program

CPGA, called XØØ8Ø in the Conversationally Oriented Real-Time Program-Generating System (CORPS) Library, is a computer program for the analysis of pile group foundation using the stiffness method. The pile cap is assumed to be rigid and the soil-pile behavior is assumed to be linearly elastic.

Coding and Data Format

CPGA is written in FORTRAN and is operational on the following systems:

a. WES Honeywell DPS/1.

b. Harris 500 computers which are located at most district Corps offices.

c. Control Data Corporation, Cybernet Computer Service's CDC CYBER systems.

Data can be input interactively at execute time or from a prepared data file with line numbers. Output may be directed to an output file or come directly back to the terminal.

How to Use CPGA

A short description of how to access the program on each of the three systems is provided below. It is assumed that the user knows how to sign on the appropriate system before trying to use CPGA. In the example initiation of execution commands below, all user responses are underlined, and each should be followed by a carriage return.

WES Honeywell System

After the user has signed on the system, the two system commands FORT and NEW bring the user to the level to execute the program. Next, the user issues the run command

RUN WESLIB/CORPS/XØØ8Ø,R

to initiate execution of the program. The program is then run as described in this user's guide. The data file should be prepared prior to issuing the RUN command. An example initiation of execution is as follows, assuming a data file had previously been prepared:

```
HIS SERIES 600 ON 03/04/81 AT 13.301 CHANNEL 5647
USER ID - ROKACASECON
PASSWORD - XXXXXXXXXXXXXX
SYSTEM? FORT NEW
READY
*RUN WESLIB/CORPS/XØØ8Ø,R
```

CDC, Cybernet System

The log-on procedure is followed by a call to the CORPS procedure file

OLD, CORPS/UN=CECELB

to access the CORPS Library. The file name of the program is used in the command

BEGIN,,CORPS,XØØ8Ø

to initiate execution of the program. An example is:

```
84/01/25 10.32.51 AC2E5DA
EASTERN CYBERNET CENTER SN487 NOS         1.4/531.281/20AD
FAMILY:  KOE
USER NAME:  CEROC2
PASSWORD -
XXXXXXX
TERMINAL:      510,NAMIAF
RECOVER/CHARGE:  CHARGE, CEXXXXX, YYYYYY
/OLD, CORPS/UN=CECELB
/BEGIN,,CORPS/XØØ8Ø
```

Local district Harris Systems

After the user has signed on the system, the command to execute the CORPS program will be

*CORPS.XØØ8Ø

An example to illustrate the log-on and execution procedure on one Harris 500 is shown below. There may be some differences at some local Corps sites.

```
"ACOE - VICKSBURG"
USER #? NNNNWES WESXXX

** Good Morning   25 Jan 84   9:56:31
VED HARRIS 500

*CORPS,XØØ8Ø
```

How to Use CORPS

The CORPS system contains many other useful programs which may be catalogued from CORPS by use of the LIST command. The execute command for CORPS on the WES system is:

```
RUN WESLIB/CORPS/CORPS,R
ENTER COMMAND (HELP,LIST,BRIEF,MESSAGE,EXECUTE, OR STOP)
*?LIST
```

On the Cybernet system, the commands are:

```
OLD,CORPS/UN=CECELB
BEGIN,,CORPS,CORPS
ENTER COMMAND (HELP,LIST,BRIEF,MESSAGE,EXECUTE, OR STOP)
*?LIST
```

On the Harris local systems, the commands are:

```
*CORPS

ARE YOU USING A PRINTER TERMINAL OR CRT?
ENTER P OR C
C

ENTER COMMAND (BRIEF,EXECUTE,LIST,HELP,STOP)
LIST
```

ELECTRONIC COMPUTER PROGRAM ABSTRACT

TITLE OF PROGRAM			PROGRAM NO.
Analysis of Pile Group (CPGA) (XØØ8Ø)			713-F3-RØØ81
PREPARING AGENCY See reverse			
AUTHOR(S) See reverse	DATE PROGRAM COMPLETED March 1987	STATUS OF PROGRAM PHASE INIT	 STAGE OP

A. PURPOSE OF PROGRAM

This computer program is for basic pile group analysis using Saul's method. The analysis uses the stiffness method with the cap assumed to be rigid and the pile-soil behavior assumed to be linearly elastic.

B. PROGRAM SPECIFICATIONS

FORTRAN

C. METHODS

Saul's Method
Stiffness method

D. EQUIPMENT DETAILS

Time sharing program, DPS-8, CDC 175, Harris 500

E. INPUT-OUTPUT

All data are to read from a prepared data file or entered interactively. Program uses free field format.

F. ADDITIONAL REMARKS

A copy of the program and documentation may be obtained from the Engineering Computer Program Library (ECPL), WES; commercial telephone (601)634-2581, or FTS 542-2581.

PREPARING AGENCY (Continued).

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J. P. Hartman, J. J. Jaeger, J. J. Jobst, Deborah K. Martin, and CASE Task Group on Pile Structures

PREFACE

This report documents and describes a computer program, CPGA, that can be used to analyze group pile foundations.

The work was sponsored through funds provided to the US Army Engineer Waterways Experiment Station (WES) by the Engineering and Construction Directorate of the Office, Chief of Engineers (OCE) under the Computer-Aided Structural Engineering (CASE) Project. This user's guide was written by the Pile Structures and Substructures Task Group of CASE for the Information Technology Laboratory (ITL), formerly the Automation Technology Center, WES. Major portions of CPGA were developed by the authors. However, some of the programming methods used are based on portions of numerous other programs developed within the Corps. John J. Jobst, US Army Engineer District, St. Louis, developed the initial program. Mrs. Deborah K. Martin, ITL, WES, provided programming support.

Specifications for the program were provided by the members of the CASE Task Group on Pile Structures and Substructures. The following were members of the task group during program development:

Mr. James Bigham, Rock Island District (Chairman)
Mr. Richard Chun, Pacific Ocean Division
Mr. Edward Demsky, St. Louis District
Mr. Joseph Hartman, Southwestern Division
Mr. John Jaeger, St. Louis District
Mr. Phil Napolitano, New Orleans District
Mr. Charles Ruckstuhl, New Orleans District
Mr. Ralph Strom, North Pacific Division

Part time members of the task group were:

Mr. Roger Brown, South Atlantic Division
Mr. Roger Hoell, St. Louis District

Mr. Don Dressler was the OCE point of contact. Dr. N. Radhakrishnan, Acting Chief, ITL, WES, was Project Manager for the CASE Project and provided overall guidance. Mr. Paul K. Senter, Project Coordinator for the work of the CASE Project, WES, monitored the work. Mr. H. Wayne Jones, Engineering Application Group, ITL, WES, was Task Group Coordinator. Information Products Division, ITL, WES, Editor Mrs. Gilda Miller did the final editing for the publication.

LTC Jack R. Stephens, EN, is the Acting Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic inches	16.38706	cubic centimetres
feet	0.3048	metres
inches	2.54	centimetres
kips	4.448222	kilonewtons
kip-feet	1355.818	newton-metres
kip-inches	112.9848	newton-metres
kips (force) per square inch	6.894757	megapascals
pounds (mass) per cubic inch	27.6799	grams per cubic centimetre
pounds (force) per square inch	6.894757	kilopascals
square inches	6.4516	square centimetres

CPG FAMILY OF PILE GROUP PROGRAMS

The computer programs listed here are part of a family of pile group programs being developed by the CASE Pile Structures and Substructures Task Group. The program CPGA performs the analysis of a pile group while the other programs perform some pre- or postprocessing function. Currently, all of these programs are not complete. Other programs may be added to the family as needs are identified.

CPGA -	PILE GROUP ANALYSIS - Performs an analysis of a pile foundation utilizing the stiffness method. Pile cap is assumed to be rigid (nondeformable). Pile-soil behavior is assumed to be linearly elastic. (Resistance is directly proportional to displacement).
CPGG - (Postprocessor)	PILE GROUP GRAPHICS DISPLAY - Provides a graphic display of geometry and analysis results from CPGA.
CPGS - (Pre- and Post- Processor)	PILE HEAD STIFFNESS MATRIX OR COMPLETE ANALYSIS OF 2-D OR 3-D VERTICAL PILES - a. Determines pile head stiffness coefficients matrix for a linearly elastic pile-soil system. b. Determines displacements, internal forces and moments, and lateral soil pressures throughout the length of a pile resulting from specific loads or displacements at the pile head.
CPGI - (Preprocessor)	PILE GROUP INTERFERENCE - Checks for geometric interference conditions which occur in a pile foundation layout.
CPGB - (Postprocessor)	PILE GROUP BASE SLAB ANALYSIS - Provides a structural analysis of the base slab or pile cap from pile loads resulting from the pile analysis.
CPGF - (Postprocessor)	PILE GROUP ANALYSIS WITH FLEXIBLE BASE - Performs an analysis of a pile foundation considering pile cap flexibility.
CPGO - (Preprocessor)	PILE GROUP OPTIMIZATION - Provides an optimal design layout of a given foundation utilizing data and analysis routings from CPGA.
CPGC - (Preprocessor)	PRESTRESSED PILE INTERACTION DIAGRAM - Provides fully supported prestressed pile interaction diagram and design load strength data required to investigate combined loadings in CPGA. Piles may be square, round, or octagonal; solid or hollow. The user selects the prestress pattern and level of prestress.

USER'S GUIDE: PILE GROUP ANALYSIS (CPGA) COMPUTER PROGRAM

PART I: USER'S MANUAL

Introduction

1. CPGA, a computer program for basic pile group analysis, was developed through the Computer-Aided Structural Engineering (CASE) Project by the Task Group on Pile Structures and Substructures. It is intended to be a simple program for pile group analysis which eliminates many of the inaccuracies inherent in the hand analysis methods. However, the program is limited because it does not account for the effects of pile cap flexibility nor nonlinear soil behavior. Part I consists mainly of the information required to run the CPGA program with some theoretical and background material also included in Part II. However, more comprehensive coverage of the theoretical methods and practical considerations of pile design is contained in the material researched for this study. Additional information will be provided in a pile theoretical manual to be developed by this same task group.

Program Summary

Analysis method

2. CPGA utilizes the stiffness method (Saul 1968) of pile group analysis. The pile cap is assumed to be rigid or nondeformable. Each pile is represented by its calculated stiffness coefficients. The stiffness coefficients of all piles are summed to determine the stiffness matrix for the total pile group. Displacements of the rigid pile cap are determined by multiplying the inverse of the group stiffness matrix by the sets of applied loads. Displacements of the rigid cap define displacements of individual pile heads, which are multiplied by the pile stiffness coefficients to determine the force acting on each pile head. These resulting loads are then compared to user-defined allowable loads. This program assumes "Long" piles (i.e., the driven pile length must be > 5T or 4R as shown in the Background Manual, paragraph 62 for details).

3. This program accounts for the effects of pile locations and batters. It can linearly represent any type of pile-soil interaction and can represent fixed or pinned interaction between the pile and pile cap. Piles can have a different axial stiffness for tension loads than for compression loads; the program will iterate to a solution using the appropriate stiffness, based on the direction of the calculated pile load.

Input data

4. The user must specify pile and soil properties, pile locations and batters, applied loads, and pile allowable loads. The pile and soil properties are used to calculate the pile stiffness coefficients, or the user can calculate the stiffness by other means and input it directly to the program. Piles of several types may be included in the same analysis. The program is limited to maximums of 800 piles and 20 load cases.

Output

5. Output may consist of any combination of the following: pile and soil properties, pile locations and batters, group and individual pile stiffness coefficients, the elastic center of a two-dimensional (2-D) pile group, displacements of any point on the pile cap, and pile forces along the pile axes or along the pile cap axes. Pile forces include shears, moments, and axial loads. The program will also summarize the comparison between calculated and allowable pile loads.

Auxiliary programs

6. Preprocessor and postprocessor programs are available to help create input data and to help interpret output. These programs are described in the preface of this report.

Program Operation

Input

7. The program asks first if input data is in a prepared data file or if it will be input interactively in response to program prompts. The user is then asked to supply a file name for the input data, already existing or to be created by the program.

```
DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
ENTER F OR I
? F
ENTER DATA FILE NAME.
? FILENAME
```

Underlines indicate user responses. If additional information is required, the program will prompt as necessary.

Interactive input

8. In the interactive input mode, the program prompts for input data in the order shown in paragraph 24. The user need only input the actual data items, and the program will automatically supply line numbers and data line headings such as "PROP" (pile properties). An asterisk (*) response to any prompt will indicate that the requested data will not be input. When the program prompts for a list (paragraph 21), all data provided will be considered part of that list. To continue input to a list, the user must type an asterisk (*) at the end of each line contained within the list. A question mark (?) response to any prompt will cause printing of a brief description of the requested data items.

```
DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
ENTER F OR I
? I
ENTER NEW DATA FILE NAME
? FILE NAME
```

Underlines indicate user responses.

Analysis

9. Once the input has been entered, an analysis is performed as described in paragraphs 2 and 3. If piles are in tension, a message is printed to indicate how many are in tension for each load case. The user may then request that an iterative analysis be performed, using different axial stiffnesses for tension piles as compared to compression piles (input data item f, paragraph 24). Details of the tension-pile interaction method are contained in Part II, paragraph 58 of this report. However, if the data check command ("DAT") is present in the data, no analysis is performed. Only a check of the data is carried out and a geometry plot file is generated, if requested.

Data revisions

10. After an analysis is complete or after all interactive input has been entered, the user may change selected items of input, update the input file, and reanalyze the new pile foundation as follows:

```
SHOULD THE INPUT FILE NAMED 'FILE NAME' BE LISTED? (Y OR N)
? N
ENTER CHANGE TO INPUT FILE OR * WHEN DONE
? DATA
? DATA
? *
DO YOU WISH TO HAVE AN ANALYSIS OF YOUR INPUT FILE? (Y OR N)
? Y
RUN CPGA AGAIN? (Y OR N)
? N
```

"DATA" represents a complete new line in the data file, including a line number. If the new line number is the same as an existing one, the existing line is replaced. If a line number only is entered, i.e., no data follow the line number, that line will then be deleted from the file. As many new data lines as required may be entered. An asterisk (*) response will end this data revision mode. Any changes are automatically saved in the permanent data file.

Reanalysis

11. After the input data changes have been made the program asks whether another analysis should be performed. A yes answer will restart the program with the request for an input file name. A no answer will stop the program.

Input Data Description

Order

12. Items should generally be input in the sequential order shown in paragraph 24. Out-of-order data items may cause fatal errors during program execution. Row, arc, duplicate, and rotate may be input and repeated in any order to describe complex pile layouts.

Format

13. When data is entered in a time sharing file, it should be in a free field format with line numbers and a blank following the line number. Numerical data must be an integer or real number format; "E" format is also

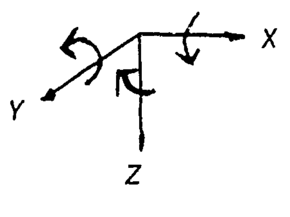
permitted. Input is limited to 80 characters per line, including the line number. If more than 80 characters are required for any data items, it may be continued on the following line, preceded by a line number. For continuation of a list, see paragraph 21. See paragraph 24 for description of specific input data and Appendix A for a summary of input data.

14. The same restrictions apply when data are entered interactively except that line numbers are supplied by the program and input is limited to 71 characters per line. The data file will then be created automatically by the program.

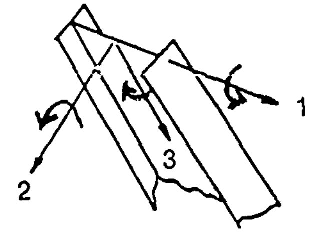
Coordinate system

15. The global coordinate system is an orthogonal right-hand system. The axes are labeled X , Y , and Z , with Z* being positive downward. The global system is used for specification of pile locations and orientations, applied forces and moments on the pile cap, and for calculation of total pile group stiffness and pile cap displacements.

16. Each pile also has its own local coordinate system with axes labeled 1, 2, and 3. The orientation of the local system is determined by the specified batter and batter direction of each pile. The 3 axis is positive along the pile length from head to tip. The 1 and 2 axes correspond to the pile principal axes, with the pile batter in the 1-3 plane. Orientation of the 1 axis with respect to the X axis is defined in data input item o, paragraph 24. The local coordinate system is used for calculation of the stiffness coefficients and forces for each pile.



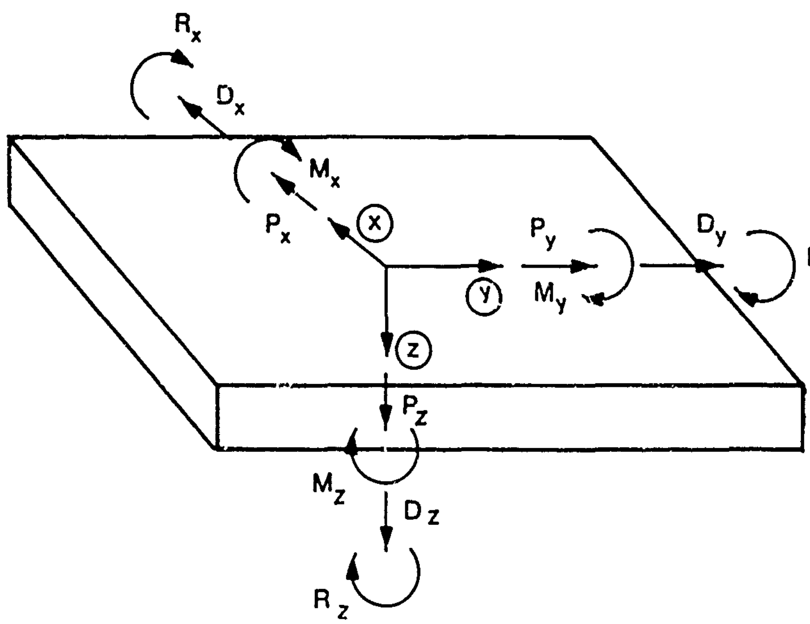
Global coordinate system



Local coordinate system

17. The letters D and R are used to represent global deflections and rotations, and the letters P and M are used to represent forces and

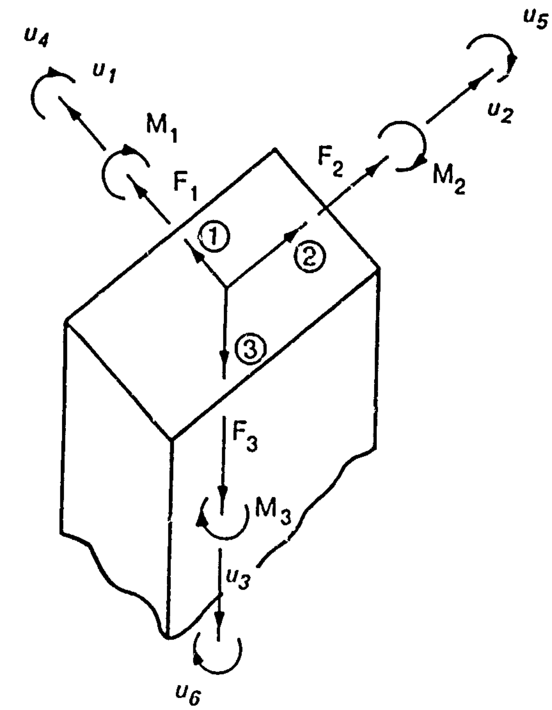
* For convenience, symbols and abbreviations are listed in the Notation (Appendix C).



$$[Q] = \begin{Bmatrix} P_x \\ P_y \\ P_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} \qquad\qquad [U] = \begin{Bmatrix} D_x \\ D_y \\ D_z \\ R_x \\ R_y \\ R_z \end{Bmatrix}$$

Global Forces and Moments   Global Deflections

<u>Global Pile Cap Forces, Moments and Deflections</u>



$$[q] = \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix}$$

Local Forces and Moments

$$[u] = \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{Bmatrix} = \begin{Bmatrix} u \\ v \\ w \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{Bmatrix}$$

Local Deflections

<u>Local Pile Head Forces, Moments, and Deflections</u>

moments, respectively. The letters D , R , P , or M are succeeded with the applicable global axis X , Y , or Z as described in paragraph 15 to indicate their direction. Similarly, for local forces and moments, the applicable local axis 1, 2, or 3 succeeds the letters F and M .

Units

18. Input data must be in English units. All information defining pile locations, lengths, heights, and tip elevations must be input in feet, applied moments in kip-feet, and all other data in kips and inches. When using "E" format, no blanks are allowed and a positive sign is optional after the "E". Thus, the number 3.0E 06 would not be interpreted as three million, while 3.0E06 and 3.0E+06 would be.

Omitting data

19. Often, not all data lines will be required to describe a given problem. In such cases, omit any unnecessary items from the input data. Some input variables will have a default value indicated. If such an item is omitted from the input, the default value will automatically be used.

Repeating data

20. It may be necessary to repeat a data line several times. For example, the "BATTER" data line would be used once for each different batter in a pile layout. If, when repeating data, conflicting data are specified, the latest value always supersedes the previous values. For example, if pile number 15 had a batter of 2:1, a subsequent use of the "BATTER" data item could change that to any other value.

Lists

21. Where "list" appears in the following input data descriptions it refers to a list of piles, load cases, or output data groups to which the previous input data apply. The list should be in the form: BATTER 2.5 3 8 10 TO 17 19 TO 23 27 ....., where "TO" indicates all piles or load cases from the preceding to the following numbers, inclusively. Long lists may be continued onto the following line or lines. When the specified information applies to all piles or all load cases, the word "ALL" may be used in place of a specific list. If "ALL" is used for the list of piles for the duplicate, rotate, or slope input (see data input items u, v, and w, paragraph 24), it refers only to those piles previously defined.

Text input

22. In the following data description, characters in quotation marks

are an integral part of a given set of input when using the input file mode. Those characters must be included along with the numerical data; the quotation marks themselves should not be included. Only one data description may be contained on a single line. For example, on data input item n, paragraph 24, only one specified pile batter "BAT" should be listed on a single line; however, the list of piles to which this data description applies may be continued onto additional lines as previously discussed in paragraph 21. Text input may be shortened to as few as three characters, if desired. When using the interactive input mode, the items in quotation marks should not be included unless obviously required, such as use of "TO" in lists.

Examples

23. Examples of input data modes and formats may be found in Appendix B, Example Problems.

Specific input data

24. A description of specific input data is given in the following paragraphs.

a. Title. A one-line title must be provided. If additional lines are required, a dash (-) at the end of each line will indicate that the title is continued on the next line, up to a maximum of five lines. The last line of the title should not end with a dash.

b. Pile properties: "PROP" E I1 I2 A C33 B66 list

E = modulus of elasticity of pile material (K/IN^2)

I1 = moment of inertia about 1 axis (IN^4)

I2 = moment of inertia about 2 axis (IN^4)

A = cross-sectional area of pile (IN^2)

C33 = axial stiffness modifier for embedded portion of pile

B66 = torsional stiffness (IN-KIP)/RAD

list = list of piles to which properties apply

NOTE: This data line may be omitted if all pile stiffnesses will be directly input as shown in data input item e, paragraph 24, or both methods may be used for different piles in the same problem. Pile stiffness is calculated from the pile and soil properties. See Part II for details of this calculation. No more than 20 pile-property sets may be specified. If necessary, this data item may be continued on the next line. For free-standing, unsupported piles, the axial stiffness modifier C_{33} applies to the portion of embedded length only (L_e). The program will combine the axial stiffness for the unsupported length (L_u) with the L_e to develop a total axial

stiffness for the entire pile length (L). The B_{66} stiffness is for the entire pile, that is, the embedded portion and any free standing portion that may exist (refer to Part II, paragraphs 63b and c).

c. Soil description: "SOIL" PSOIL ESOIL LENGTH L LU list

PSOIL = "ES" or "NH"

ESOIL = value of subgrade modulus (ES), (K/IN^2), or value of the constant of horizontal subgrade reaction (NH) (K/IN^3)

LENGTH = "LEN" or "TIP"

L = total length of pile, including L_u plus the L_e, if "LEN" is specified (FT). If "TIP" is specified, L is the Z coordinate of the pile tip and the length is calculated by the program (FT).

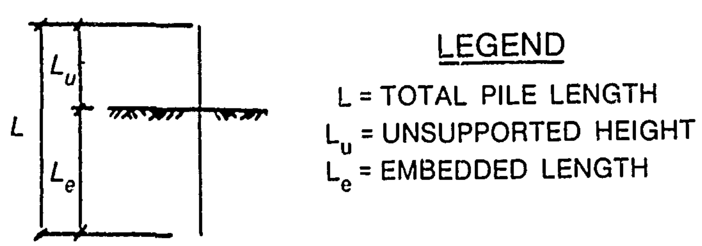
LU = unsupported length of pile above the groundline (FT).

list = list of piles to which the soil description applies.

NOTE: This data line may be omitted if all pile stiffnesses will be input directly, as shown in data input item e, paragraph 24. When pile properties are specified for a given pile, the soil description must also be provided. No more than 20 soil-description sets may be specified. ES = $K_h B$, where K_h is the coefficient of horizontal subgrade reaction (K/IN^3), and B is the pile width (IN). ES (K/IN^2) represents the force per unit length of pile which would cause a unit lateral displacement. When ES is specified, it is assumed to be constant along the entire length of the pile.

NH = dES/dZ, the variation of ES with depth (K/IN^3). When NH is specified, ES is assumed to vary linearly along the depth of the pile, starting from zero at the groundline.

The unsupported height of pile (L_u) is the vertical distance from the groundline to the base of the structure as shown below.



The pile stiffness is calculated from the pile and soil properties. Part II gives details of this calculation. The pile stiffness is calculated for the unsupported condition using the assumption that there is no cross bracing between piles, that each pile acts independently as a cantilever above the ground.

d. Fixity: "PIN" or "FIX" list

list = list of piles which are pinned or fixed to the structure.

NOTE: This data line may be omitted for all piles which have a pinned connection to the structure. A pinned connection is one which is assumed to transfer no moments through that connection. Pinned or fixed has no effect on piles for which the bIJ values are input.

e. Pile stiffness: "BIJ" B11 B22 B33 B44 B55 B66 B15 B24 list

B11, B22 = lateral stiffness along 1 axis and 2 axis

B33 = axial stiffness

B44, B55 = rotational stiffness about 1 axis and 2 axis

B66 = torsional stiffness

B15, B24 = coupling stiffness, moment required to cause unit lateral displacement, or force required to cause unit rotation

list = list of piles to which the specified stiffness coefficients apply

NOTE: This data line may be omitted if all pile stiffnesses will be calculated based on the pile and soil properties as specified in data input items b, c, and d, paragraph 24.

The BIJ pile stiffness should include the complete stiffness for the embedded and free-standing pile lengths, where applicable.

All BIJ terms are in units of kips and inches. If this data line requires more than one line, continue any data on following lines as required.

This data line may be repeated as required, to specify different stiffnesses for different piles. If more than one stiffness matrix is specified for the same pile, the last matrix always supersedes all those previously specified for the pile.

No more than 40 different sets of pile stiffness may be specified.

f. Tension pile stiffness modifier: "TENSION" CT list

CT = axial stiffness modifier for a pile in tension, default = 1.0

list = list of piles to which modifier applies

NOTE: This data line may be omitted if an iterative solution will not be requested for piles in tension, paragraph 9. Part II, paragraph 58 gives a description of this solution method. The usual pile axial stiffness is B33 which is input directly or is calculated from pile properties as B33 = C33 × (AE/L). If an iterative solution is requested, B33 is replaced with B33T for each pile in tension, where B33T = CT(B33) .

g. Allowable loads steel and timber piles: "ALLOW" SHAPE AC AT ACC ATT AM1 AM2 list

SHAPE: "R" = round piles, "H" = H piles

AC = allowable pile compression load (KIPS)

AT = allowable pile tension load (KIPS)

ACC = allowable axial compression load for the combined bending and axial load check (KIPS)

ATT = allowable axial tension load for the combined bending and axial load check (KIPS)

AM1 = allowable moment about 1 axis (IN-KIPS)

AM2 = allowable moment about 2 axis (IN-KIPS)

list = list of piles to which allowable loads apply

NOTE: All allowables are in terms of forces and moments, not in terms of stresses and are input as absolute values.

The following comparisons are made:

$$\left(\frac{F3}{AC}\right)\left(\frac{1}{OSF}\right) \le 1.0 \tag{1}$$

$$\left(\frac{-F3}{AT}\right)\left(\frac{1}{OSFT}\right) \le 1.0 \tag{2}$$

$$\left[\frac{F3}{ACC} + MF1\left(\frac{|M1|}{AM1}\right) + MF2\left(\frac{|M2|}{AM2}\right)\right]\left(\frac{1}{OSF}\right) \le 1.0 \tag{3}$$

$$\left[\frac{-F3}{ATT} + \frac{|M1|}{AM1} + \frac{|M2|}{AM2}\right]\left(\frac{1}{OSFT}\right) \le 1.0 \tag{4}$$

$$\left[\frac{F3}{ACC} + \left(\frac{MF1}{AM1}\right)\sqrt{M1^2 + M2^2}\right]\left(\frac{1}{OSF}\right) \le 1.0 \tag{5}$$

$$\left[\frac{-F3}{ATT} + \left(\frac{1}{AM1}\right)\sqrt{M1^2 + M2^2}\right]\left(\frac{1}{OSFT}\right) \le 1.0 \tag{6}$$

F3 is the calculated pile axial force and M1 and M2 are the bending moments about the two pile axes. The calculated pile forces and moments are based on service-load conditions. Equations 5 and 6 are used for round piles where MF1 = MF2 and AM1 = AM2 . OSF and OSFT are the allowable overstress factors defined in data input item m, paragraph 24. The moment magnification factors (MF1, MF2) are equal to 1.0 for fully supported piles and are computed from data supplied in data input item j, paragraph 24 for unsupported piles. Fully embedded piles in very weak soil may be considered as unsupported (Part II, paragraphs 43 and 44).

h. Design load strengths--prestressed concrete or reinforced concrete piles: "DLS" SHAPE AC AT PO PT PB MB MO ST W list

SHAPE: "R" = round or octagonal piles, "S" = square piles

AC and AT are as defined in input item g, paragraph 24

PO = axial design load strength of piles in compression (KIPS)

PT = axial design load strength of piles in tension (KIPS)

PB = axial design load strength at balanced conditions (KIPS)

MB = design moment strength at balanced conditions (IN-KIPS)

MO = design moment strength under pure flexure (IN-KIPS)

ST = structure type; "H" = hydraulic structure, "N" = nonhydraulic structure

W = diameter of round pile or width of square pile (IN)

list = list of piles to which the design load strengths apply

In addition to Equations 1 and 2, the following comparisons are made for prestressed concrete and reinforced concrete piles for service-load conditions.

For F3 > PB/SF

$$\left[\frac{[(SF)(F3) - PB]}{(PO - PB)} + \frac{(SF)(MF1)\sqrt{M1^2 + M2^2}}{(K)(MB)}\right]\frac{1}{OSF} \leq 1.0 \qquad (7)$$

For 0 ≤ F3 < PB/SF

$$\left[\frac{PB - SF(F3)}{PB + \dfrac{PB(MO)}{(MB - MO)}} + \frac{SF(MF1)\sqrt{M1^2 + M2^2}}{K(MB)}\right]\frac{1}{OSF} \leq 1.0 \qquad (8)$$

For F3 < 0

$$\left[\frac{SF(-F3)}{PT} + \frac{SF\sqrt{M1^2 + M2^2}}{K(MO)}\right]\frac{1}{OSFT} \leq 1.0 \qquad (9)$$

where

SF = safety factor

SF = 2.7 for hydraulic structures

SF = 2.5 for structures other than hydraulic structures.

F3 , M1 , and M2 are as described previously. All equations are based on round pile formulas. If a pile is designated as round or octagonal (SHAPE = R), the biaxial bending capacity equals the uniaxial bending capacity about the principle axis and the value of K in Equations 7 through 9 is equal to 1. If a pile is designated as square (SHAPE = S), the biaxial moment capacity is equal to the uniaxial bending capacity multiplied by a reduction factor K .

where

$$K = 1 - (A/45)(0.15)$$

For $|M1| \geq |M2|$, $A = \tan^{-1}(|M2|/|M1|)$;

For $|M1| < |M2|$, $A = \tan^{-1}(|M1|/|M2|)$

Equations 7 and 8 are valid only if the actual resultant bending moment, $\sqrt{M1^2 + M2^2}$ is greater than F3 × EMIN where EMIN = 0.1W. In Equations 7 and 8, F3 × EMIN is substituted for $\sqrt{M1^2 + M2^2}$ when F3 × EMIN > $\sqrt{M1^2 + M2^2}$.

i. Allowable stress check--prestressed concrete piles: "ASC" SHAPE A S FPC IPC FA FT list

SHAPE: "S" = square piles, "R" = round or octagonal piles

A = cross-sectional area of pile (IN^2)

S = section modulus of pile about either #1 or #2 axis (IN^3)

FPC = concrete stress due to final prestress force (KSI)

IPC = concrete stress due to initial prestress force (KSI)

FA = allowable compressive stress in concrete (KSI)

FT = allowable tensile stress in concrete (KSI)

list = list of piles to which allowable stress data apply

NOTE: Allowable stresses FA and FT are input as absolute values.

The following comparisons are made for square piles (SHAPF = S);

$$\left[\frac{F3}{A} - \frac{|M1|}{S} - \frac{|M2|}{S}\right]\left(\frac{1}{OSFT}\right) + FPC \geq -FT \qquad (10)$$

$$\left[\frac{F3}{A} + \frac{(MF1)|M1|}{S} + \frac{(MF2)|M2|}{S}\right]\left(\frac{1}{OSF}\right) + IPC \leq FA \qquad (11)$$

and for round or octagonal piles (SHAPE = R):

$$\left[\frac{F3}{A} - \frac{\sqrt{M1^2 + M2^2}}{S}\right]\left(\frac{1}{OSFT}\right) + FPC \geq -FT \tag{12}$$

$$\left[\frac{F3}{A} + \frac{(MF1)\sqrt{M1^2 + M2^2}}{S}\right]\left(\frac{1}{OSF}\right) + IPC \leq FA \tag{13}$$

The comparisons made in Equations 10 through 13 are to check that actual stresses are within allowable limits at service-load conditions. The actual pile stress (left-hand side of Equations 10-13) is output for prestressed concrete piles. The comparisons are made assuming the pile properties are the same about both principal axes.

j. Unsupported pile data: "UNSUP" MATL CM1 CM2 PCR1 PCR2 ST list

MATL: "S" = steel, "T" = timber, "C" = concrete

CM1, CM2 = moment diagram shape factor for the 1 and 2 axes, respectively

PCR1, PCR2 = critical load for buckling about the 1 and 2 axes, respectively (KIPS)

ST = structure type; "H" = hydraulic structures, "N" = nonhydraulic structures

list = list of piles to which unsupported pile data apply

NOTE: CM1 and CM2 are moment diagram shape factors. For guidance on appropriate values for CM1 and CM2, see the AISC or ACI codes.

If buckling is of no concern, this data item may be omitted. The moment magnification factors for bending are based on the following equations.

$$MF1 = \frac{CM1}{1 - F3\left(\frac{SF}{PCR1}\right)} \geq 1$$

$$MF2 = \frac{CM2}{1 - F3\left(\frac{SF}{PCR2}\right)} \geq 1$$

where SF equals safety factor. The appropriate SF depends on material type and structure type (Part II, Table 1). When the moment magnification factor is less than 1.0, a value of 1.0 is used. The moment magnification factor equations are

valid only for values of F3 that are less than the critical buckling load divided by the appropriate SF (F3 < PCR1/SF and F3 < PCR2/SF). When the actual pile force, F3 , is greater than the critical buckling load divided by the appropriate SF (PCR/SF), the safe buckling capacity is exceeded and the moment magnification factor becomes negative. For this condition, a "B" is output for the combined bending factor and no other allowable checks are made.

k. Design moment factors for pinned pile: "PMAXMOM" KMP1 KMP2 list

KMP1 = moment factor for M1 (See note) (IN)

KMP2 = moment factor for M2 (See note) (IN)

list = list of piles to which factors apply

NOTE: This data line may be omitted if all piles are fixed. (i.e., piles which transfer moment to the pile cap, those piles which have nonzero values for B44 and B55.) For pinned piles, the maximum moments occur at some points along the pile length and the moment values used to compare to allowables will be calculated as:

$$M1 = KMP1 \times F2$$

$$M2 = KMP2 \times (-F1)$$

where F1 and F2 equal calculated pile shear forces. If this data item is omitted, the program calculates the values of KMP1 and KMP2 automatically, as shown in Part II, paragraphs 33 through 57. If however, the pile stiffness is input by bij terms, data input item e, paragraph 24, then KMP1 and KMP2 must be input, or the stress check is not performed due to insufficient soil and pile input data, and an error message is printed. Care should be taken when using the moment factors since the locations of maximum moments for the two pile axes are not identical, and neither maximum moment location is necessarily the critical point for design. Up to 20 different sets of maximum moment factors may be specified.

l. Moment factors for fixed unsupported piles: "FUNSMOM" KMF1U KMF2U list

KMF1U = moment factor for M1U , (see note) (IN)

KMF2U = moment factor for M2U, (see note) (IN)

list = list of piles to which the moment factors apply

NOTE: This input item applies only to fixed piles extending above the groundline. If this input item is omitted, the additional analysis check noted below is not performed. For piles extending above the groundline and fixed to the pile cap, the critical design moment may occur at the pile head or along the

pile length. The moment factors for fixed, unsupported piles are similar to the design moment factors for pinned piles, data input item k, paragraph 24, but since the piles are fixed and have moments at the pile head, the following equations are used:

$$M1U = M1 + KMF1U \times F2$$

$$M2U = M2 - KMF2U \times F1$$

where F1 , F2 and M1 , M2 equal calculated shears and moments at the pile head. The new moments M1U and M2U are checked using the same equations and allowable stresses as for M1 and M2 . Then, in the pile forces output, an additional line will appear showing the values of M1U , M2U , and the stress factor calculated using these moments.

m. Overstress factors: "FOVSTR" OSF OSFT list

OSF = overstress factor allowed, default = 1.0

OSFT = overstress factor allowed for pile tension load, default = 1.0

list = list of load cases to which overstress factors apply

NOTE: This data line may be omitted and the default values of 1.0 will be used. See data input items g, h, and i, paragraph 24, above for application of overstress factors. Up to five different overstress factor sets may be specified.

n. Pile batter: "BATTER" BAT list

BAT = slope ratio of batter: vertical/horizontal, default = 100

list = list of piles to which batter applies

NOTE: This data line may be omitted and the pile will be assumed to be vertical. When BAT = 100 or BAT = 0 , the pile is assumed to be exactly vertical. Any number of different batters may be specified.

o. Angle to batter direction: "ANGLE" ANG list

ANG = angle (degrees) between the positive global X axis and the direction of the pile batter, i.e., the direction of the 1 axis as projected on the global XY plane, default = 0.0

list = list of piles to which the batter angle applies

NOTE: This data line may be omitted and the default value of zero will be used. A positive angle is defined by the right-hand rule about the global Z axis. Any number of different angles may be specified.

p. Pile coordinates: "PILE" PN1 X1 Y1 Z1 PN2 X2 Y2 Z2

PN_n = pile number

X_n, Y_n, Z_n = X, Y, Z coordinates of pile (FT)

NOTE: As many pile coordinates as desired can be combined on one line or listed on separate lines. However, each new line of pile coordinates must begin with a pile number, not with an X, Y, or Z coordinate. Up to 800 piles may be specified. Pile coordinates need not be specified in the same sequence as pile numbers (i.e., pile 17 could be specified before pile 14). However, after all pile coordinate and pile generation is complete (input data items p through u in paragraph 24) the piles must be numbered consecutively from one through the number of piles (i.e., if there are 27 piles they must have numbers 1 through 27).

q. Pile row generation: "ROW" AXIS NP PN1 SP1 SP2

AXIS = axis to which the row is parallel "X or Y"

NP = number of piles in row, including PN1

PN1 = pile number of first pile in row

SPn = list of pile spacings (NP-1) (FT)

NOTE: This data line may be omitted if the pile layout is not going to be generated.

NOTE: NP-1 piles are generated at specified spaces from PN1 along the indicated axis. The piles are numbered PN1 + 1 , PN1 + 2 , etc. PN1 must have been defined by specified pile coordinates in data input item p, paragraph 24. The list of pile spacings may be shortened by using the word "AT" for equal spaces. For example, 5 AT 6.5 would indicate five spaces of 6.5 ft. Such repeat factors may be embedded at any point in the list. Spacings may be positive or negative along the specified axis.

r. Repeat rows of piles: "REPEAT" NR SP1 SP2

NR = number of rows, including the original row

SPn = list of row spacings (NR-1) (FT)

NOTE: This data line may be omitted if the pile layout is not going to be generated. This line must immediately follow the definition line of the row which is to be duplicated. The row of NP piles will be duplicated NR-1 times at specified spaces to either side of the initial row. The list of row spacings may be shortened by using a repeat factor for equal spaces. For example, 4 AT -7.5 would indicate four spaces of 7.5 ft in the negative direction along the X or Y axis. The piles created follow the same numbering scheme as the original row, incrementing each pile number by one. The "REPEAT" line is not required if only the original row is desired.

s. Pile arc generation: "ARC" CENTER RAD ANG PN1 NP SP1 SP2

CENTER = X, Y, and Z coordinates of center of curvature (FT)

RAD = radius of arc (FT)

ANG = angle to PN1 from a line through CENTER parallel to the X global axis (DEG)

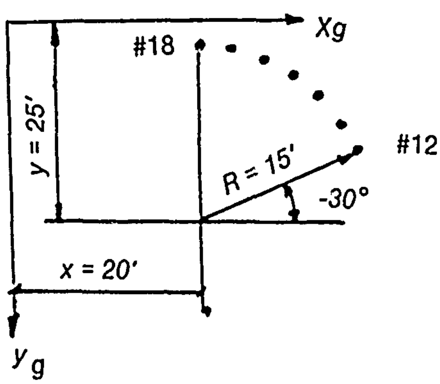
PN1 = pile number for first pile in arc

NP = number of piles in arc, including PN1

SPn = list of pile spacings along arc (NP-1) (DEG)

NOTE: This data line may be omitted if the pile layout is not going to be generated. NP-1 piles are generated along the arc. The piles are numbered PN1 , PN1 + 1 , PN1 + 2 , etc. The list of pile spacings may be shortened by using a repeat factor for equal spaces. For example, 5 AT 15.0 would indicate five spaces of 15 deg. Such repeat factors may be embedded at any point in the list. ANG and SPn may be positive or negative angles. A positive angle is defined by the right-hand rule about the Z global axis.

Example: ARC 20. 25. 0. 15. -30. 12 7 6 AT - 10.



t. Repeat arcs of piles: "REPEAT" NA SP1 SP2

NA = number of arcs, including the original arc

SPn = list of arc spacings (NA-1) (FT)

NOTE: This data line may be omitted if the pile layout is not going to be generated. This line must immediately follow the definition line of the arc which is to be duplicated. This line will generate a set of concentric arcs of NP piles with piles at intersections of radial lines and arc lines. The list of arc spacings may be shortened by using a repeat factor for equal spaces. For example, 4 AT -5.0 would indicate four spaces of 5 ft with a decreasing radius. The piles created follow the same numbering scheme as the original arc, incrementing each pile number by one. The "REPEAT" line is not required if only the original arc is desired.

u. Duplicate pile zones: "DUP" PN COORD AXIS list

PN = pile number for first duplicated pile to be generated

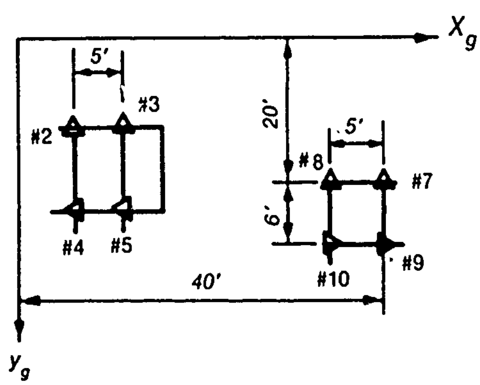
COORD = new X, Y, and Z coordinates for first pile generated in list (FT)

AXIS = axis specification for mirror image, "X" or "Y" or "N"

list = list of pile numbers to be duplicated

NOTE: This data line may be omitted if the pile layout is not to be generated. This line creates duplicates of spacings and pile properties for the listed pile numbers. These piles follow the same numbering scheme as the originals, with the first pile being numbered PN . The duplicate piles maintain the same relative positions to each other as the original piles. If AXIS = "X" or "Y" , the duplicate piles are a mirror image of the originals, rotated about a line through PN parallel to the specified axis. If AXIS = "N" , no mirroring occurs and all duplicate piles are a simple translation of the original piles.

Example: DUP 7 40. 20. 0. Y 2 TO 5



v. Rotate pile zones: "ROT" X Y ANG list

X, Y = X and Y coordinates of center of rotation (FT)

ANG = angle of rotation (DEG)

list = list of piles in zone to be rotated

NOTE: This data line may be omitted if pile zones are not to be rotated. This line repositions existing piles, it does not create new piles. All listed piles form a zone which is rotated about a point with the X, Y coordinates as specified. All piles maintain the same relative position in the zone as it rotates. Positive angle of rotation is defined by the right hand rule about the global Z axis.

w. Sloped base description: "SLOPE" PLANE SLP AXY AZ list

PLANE = plane in which the slope exists, "XZ" or "YZ"

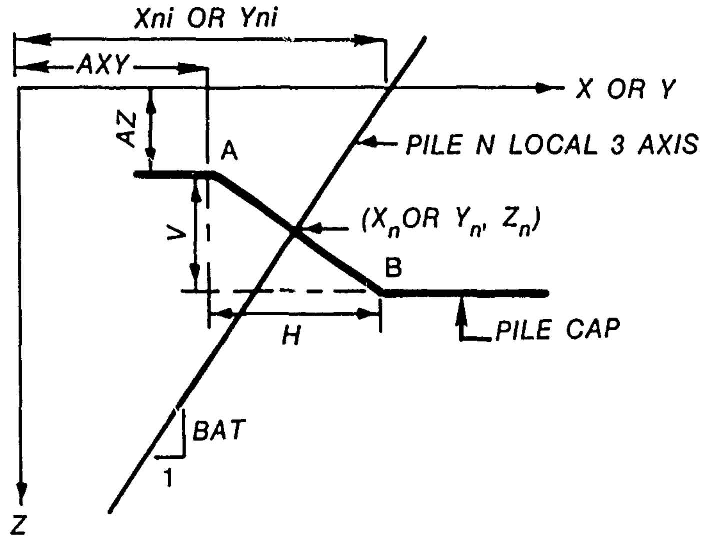
SLP = slope of pile cap (SLP = H/V)

AXY = X or Y coordinate of point "A"

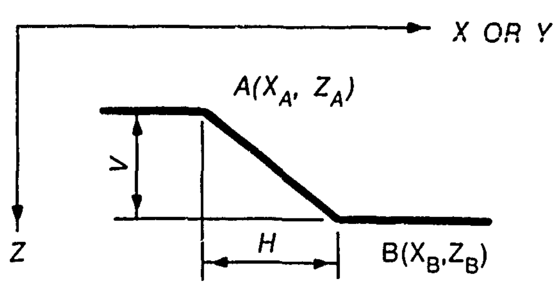
AZ = Z coordinate of point "A"

list = list of piles to which the slope applies

NOTE: This data line may be omitted if the pile cap base is not sloped. When the "SLOPE" line is used, the Z coordinate and X or Y coordinates of all piles in the list are computed at the intersection of the pile local 3 axis and the sloping pile cap. Pile coordinates, X_{Ni} , or Y_{Ni} , are initially input along the X or Y axis in data input items p through v, paragraph 24.



Pile N, local 3 axis is along the pile length and its direction is specified in data input line n, paragraph 24. SLP = H/V establishes the direction of the foundation between points A and B and AXY and AZ establish the location. The program solves for the intersection of the pile local 3 axis and the foundation. The coordinates of the intersection point are the true coordinates, X_N or Y_N , Z_N , for pile N. The slope at the cap must be contained in a single plane X-Z or Y-Z and remain constant when projected normal to that plane. The sign of SLP is determined as follows:



$H = X_B - X_A$

$V = Z_B - Z_A$ $\qquad$ $SLP = \frac{H}{V}$

x. Pile deletion: "DELETE" RENUM IPRI list

RENUM = "REN" or "NREN" (Default = "NREN")

IPRI = "Y" to print resequencing

= "N" not to print

list = list of piles to be deleted

NOTE: This data line may be omitted if no piles are to be deleted. Deleted piles remain in the pile layout definition under data input items n through t, paragraph 24. However, their stiffness is reduced to zero by the program. If "NREN" is specified, by default or by actual input, the original pile-numbering scheme is retained and deleted piles do not appear in the output. When "REN" is specified, the program renumbers the piles consecutively, omitting any piles which have been deleted in the list. All output now will be based on the revised pile numbers. A table of old pile numbers versus new pile numbers is printed if IPRI = "Y" and RENUM = "REN" ; IPRI is input only if RENUM = "REN" .

y. Load cases: "LOAD" LCN PX PY PZ MX MY MZ

LCN = load case number

PX, PY, PZ = applied forces along the X, Y, and Z axes (KIPS)

MX, MY, MZ = applied moments at the origin of the global coordinate system about the X, Y, and Z axes (FT-KIPS)

NOTE: Load case numbers need not be consecutive. As many as 20 load cases may be specified. If necessary, this data item may be continued onto the next line.

z. Specified pile cap displacements: "DISP" TYPE D list

TYPE = displacement to be specified, one of the 6 global translations or rotations, "DX" , "DY" , "DZ" , "RX" , "RY" , or "RZ"

D = magnitude of specified translation or rotation, inches if translations, degrees if rotations

list = list of load cases to which displacements apply

NOTE: This data line may be omitted if no displacements will be specified. Only one type of displacement may be specified on a single line, e.g., DISP DX 0.5 4 6 would specify an X translation of 0.5 for load cases 4 and 6. Any displacements not specified remain free to move based on applied loads and pile stiffness. Part II, paragraph 82, gives details of the solution technique for specified displacements. Specified displacements are relative to the pile group global origin.

aa. Output at terminal: "TOUT" list

list = list of output data groups to be printed at user's terminal (Default = 1, 3, 4, 6)

NOTE: If both data lines, paragraphs aa and bb are omitted, output data groups 1, 3, 4, and 6 are printed at the users terminal.

Output data groups:

(1) Pile and soil properties

(2) Pile locations and batters

(3) Pile group stiffness matrix

(4) Pile cap displacements

(5) Local forces acting on selected piles

(6) Forces acting on overstressed piles

(7) Pile forces in global coordinates

The content of these data groups is described below in paragraphs 26 through 32. The format of the "list" is described in paragraph 21. When output is requested for output data groups 1, 4, or 5 in the above list, specific coordinates or pile numbers must also be input as described below for data input in paragraphs 24cc, dd, and ee, respectively.

bb. Output to file: "FOUT" list OFN

list = list of output data groups to be written to an output file (Default = 1, 3, 4, 6)

OFN = output file name

NOTE: This data line may be omitted if output will not be written to a file. Output data groups must be identified in the same manner as those to be printed at the terminal (see data input item aa, paragraph 24). If output is requested for data groups 1, 4, or 5, further information must be provided as described below in data input items cc through ee, found in paragraph 24. If OFN is contained in the data file the user will not be prompted to provide an output file name.

cc. Pile stiffness output: "PSO" list

list = list of piles for which the pile stiffness matrix will be output (Default = pile 1)

NOTE: This input should be provided only if output data group 1 has been requested by data input item aa or bb, paragraph 24. When several piles have the same stiffness matrix, only one of those pile numbers should appear in the above list. The stiffness matrix output is the matrix as calculated from input pile and soil properties, or as input as bij terms by the user.

dd. Pile cap displacement output: "PCDO" X1 Y1 Z1, X2 Y2 Z2

Xn Yn Zn = coordinates of points on the pile cap for which displacements will be calculated (FT) (Default = None)

NOTE: This input should be provided only if output data group 4 has been requested by data input items aa and bb, paragraph 24. No more than 20 sets of coordinates may be specified. When continuing sets of coordinates onto additional lines, each new line must begin with an X coordinate. When group 4 output is requested, the three translations and three rotations at the global origin are automatically output. This output request, PCDO , is only to specify locations other than the origin for which displacements should be calculated.

ee. Pile force output: "PFO" list

list = list of piles for which local pile head forces will be output (Default = none)

ff. Pile location and batter: "PLB" list

list = list of piles for which pile geometry will be output (Default = geometry output for all piles)

NOTE: This input should be provided only if output data group 2 has been requested by data input items aa and bb found in paragraph 24.

gg. Plot file output: "FPL" PFN

PFN = plot file name for program CPGG

NOTE: If this input item is contained in the data file, the user will not be prompted to provide a plot file name for CPGG.

hh. Data check run: "DAT"

NOTE: If this input item is contained in the data file, CPGA will not perform an analysis. It will check only to ensure all pile data are input correctly and will write information to a plot file if the "FPL" command (data item gg) is contained in the data file.

Output

Output control

25. Output may be routed to the user's terminal, to an output file, or to both. The user must specify his output requirements as part of the input data. This is done by using data input items aa or bb, as described in paragraph 24.

a. Output data groups may be requested according to the following list:

(1) Pile and soil properties

(2) Pile locations and batters

(3) Pile group stiffness matrix

(4) Pile cap displacements

(5) Local forces acting on selected piles

(6) Forces acting on overstressed piles

(7) Pile forces in global coordinates

b. The content of these data groups is described in the following paragraphs. The format of the output can be seen in Appendix B, Example Problems.

Output description

26. "Pile and Soil Properties" consist of an echo of the properties and stiffness coefficients input by the user. The stiffness coefficients are printed only for those piles selected by the user, paragraph 24cc.

27. "Pile locations and batter" consist of an echo of pile head locations, the batter and direction of batter, pile length, and fixity condition. If pile properties have been input, the length of the pile and the sum of all pile lengths is printed for cost estimating purposes.

28. "Pile group stiffness matrix" consists of the calculated 6 by 6 stiffness matrix of the group. The elastic center coordinates for 2-D problems are also printed.

29. "Pile cap displacements" consist of the three translations and three rotations of the origin of the global coordinate system and the three translations of any points specified by the user, paragraph 24dd (Stoll 1972) in the global system.

30. "Local forces acting on selected piles" consist of the three forces and three moments, in the local coordinate system, acting on the head of any piles specified by the user, paragraph 24ee (Scott 1981). An axial load factor (ALF) and combined bending factor (CBF) are printed for all piles. The ALF represents the left side of Equation 1 or 2, while the CBF represents the left side of Equation 3, 4, 5, 6, 7, 8, or 9. For prestressed concrete piles, actual stresses are also printed. ASC is the maximum compressive stress (or minimum tensile stress) represented by the left side of Equation 11 or 13, and AST is the maximum tensile stress (or minimum compressive stress) represented by the left side of Equation 10 or 12. Tensile stress is negative and compressive is positive. In addition, an "*" is printed next to the pile number for any pile that does not meet all the criteria requirements expressed by Equations 1 through 13, a "#" sign is printed with the CBF for concrete piles when the moment is based on minimum eccentricity requirements. A "B" is

printed for the CBF for unsupported piles when the actual axial pile force exceeds the safe buckling capacity. For fixed, partially embedded piles, two sets of local force data are printed for each pile. The first line represents the forces at the pile cap and the second line represents the forces below the groundline at the point of maximum moment.

31. "Forces acting on overstressed piles" are the same as above but are printed automatically for all overstressed piles. Allowable loads and overstress factors are also printed.

32. "Piles forces in global coordinates" consist of the three forces and three moments in the global coordinate system, acting on the head of all piles. This data is generally used for subsequent analysis of the internal forces in the pile cap.

PART II: BACKGROUND MANUAL

Allowable Load Comparisons

Guide for checking

33. Data input items g and h in paragraph 24 are used to check allowable axial loads and moments in individual piles, input data item i is used to check allowable stresses in prestressed concrete piles, and item j is used to compute the moment magnification factors required for the above checks when the individual piles are unsupported. A pure axial load check is made based on the following equations:

$$\left(\frac{F3}{AC}\right)\left(\frac{1}{OSF}\right) \leq 1.0 \qquad \text{(1 bis)*}$$

$$\left(\frac{-F3}{AT}\right)\left(\frac{1}{OSFT}\right) \leq 1.0 \qquad \text{(2 bis)}$$

where

AC and AT = allowable axial compressive and tensile loads

= the area of the pile times the allowable axial stress or as limited by the soil properties

F3 = actual axial load (positive equals compression)

These allowable loads may be modified for selected load cases by specification of overstress factors as described in data input item m, paragraph 24. The overstress factor (OSFT) will modify the allowable pile tension load ($-F_3$), and the overstress factor (OSF) will modify all other loads. For usual load cases, OSF = OSFT = 1.0 . For unusual or short duration cases, OSF = 1.33 is generally used.

Interaction equations

34. The interaction method is used to investigate combined loadings. The actual bending moments (multiplied by a moment magnification factor to account for the P • Δ effect for unsupported piles) and the actual axial loads are compared to the bending and axial loads that would cause failure. The

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* "bis" is the standard term used to call attention to the occurrence of an item used previously.

value on the left side of Equations 3 through 9 is referred to as the combined bending factor and is listed in the output along with the calculated piles forces.

35. The actual moments used in the interaction equations are the maximum moments in each pile for the load condition under evaluation. For pinned piles, the maximum moment occurs some distance below the groundline. For fixed piles, the maximum moment can occur at the pile cap or some distance below the groundline. For fixed piles, therefore, a combined bending factor is determined for both the pile moment at the cap and for the maximum moment below the groundline.

36. The effects of slenderness on unsupported pile strengths are approximated by multiplying the pile moments by a moment magnifier, MF , data input item j, paragraph 24. MF is a function of the ratio of the axial load in the pile to the assumed critical load of the pile, the ratio of the pile moment at the cap and the maximum moment below the groundline, and the deflected shaped of the pile. The moment magnifier method used in the interaction equations is subject to the same limitations described in the American Institute of Steel Construction (AISC), Specifications for the Design, Fabrication and Erection of Structural Steel for Buildings and American Concrete Institute (ACI), Building Code Requirements for Reinforced Concrete (ACI 318-83).

37. Investigation for combined bending and axial load using the following interaction equations based on service-load conditions and working-strength methods are shown below for steel and timber piles.

<u>Steel H-piles:</u>

<u>Axial compression and bending</u>

$$\left[\frac{F3}{ACC} + MF1\left(\frac{|M1|}{AM1}\right) + MF2\left(\frac{|M2|}{AM2}\right)\right]\left(\frac{1}{OSF}\right) \le 1.0 \qquad (3\ bis)$$

<u>Axial tension and bending</u>

$$\left[\frac{-F3}{ATT} + \frac{|M1|}{AM1} + \frac{|M2|}{AM2}\right]\left(\frac{1}{OSFT}\right) \le 1.0 \qquad (4\ bis)$$

Round timber and steel pipe piles:

Axial compression and bending

$$\left[\frac{F3}{ACC} + \left(\frac{MF1}{AM1}\right)\sqrt{M1^2 + M2^2}\right]\left(\frac{1}{OSF}\right) \leq 1.0 \qquad (5\text{ bis})$$

Axial tension and bending

$$\left[\frac{-F3}{ATT} + \left(\frac{1}{AM1}\right)\sqrt{M1^2 + M2^2}\right]\left(\frac{1}{OSFT}\right) \leq 1.0 \qquad (6\text{ bis})$$

where

F3 = actual axial load

M1 = actual bending moment about the 1 axis

M2 = actual bending moment about the 2 axis

ACC = allowable axial load in compression

ATT = allowable axial load in tension

AM1 = allowable bending moment about the 1 axis

AM2 = allowable bending moment about the 2 axis

OSF = overstress factor

OSFT = overstress factor for piles in tension

MF1 and MF2 are moment magnification factors about the 1 and 2 axes that account for the P $\cdot$ Δ effect in unsupported piles. For fully supported piles, MF1 and MF2 are equal to one.

The allowable bending moments about both pile axes, AM1 , AM2 , are calculated in the conventional manner for the appropriate pile material. For example, the allowable moment is the section mo··lus multiplied by the allowable bending stress, AM1 = S1 $\times$ Fb . The allowable compression and tension forces for axial load, plus bending, ACC and ATT , are determined by multiplying the area of the pile by its allowable axial stress for that condition.

38. Concrete and prestressed concrete piles, in addition to Equations 1 and 2, are investigated for combined bending and axial load using the following interaction equations based on service-load conditions and ultimate strength methods.

Round or octagonal prestressed concrete and reinforced concrete piles:

Axial compression and bending

For F3 > PB/SF

$$\left[\frac{[(SF)(F3) - (PB)]}{(PO - PB)} + \frac{(SF)(MF1)\sqrt{M1^2 + M2^2}}{(K)(MB)}\right]\frac{1}{OSF} \leq 1.0 \qquad (7\ \text{bis})$$

For $0 \leq F3 < PB/SF$

$$\left[\frac{PB - (SF)(F3)}{PB + \dfrac{PB(MO)}{(MB - MO)}} + \frac{SF(MF1)\sqrt{M1^2 + M2^2}}{K(MB)}\right]\frac{1}{OSF} \leq 1.0 \qquad (8\ \text{bis})$$

Axial tension and bending

For F3 < 0

$$\left[\frac{SF(-F3)}{PT} + \frac{SF\sqrt{M1^2 + M2^2}}{K(MO)}\right]\frac{1}{OSFT} \leq 1.0 \qquad (9\ \text{bis})$$

where

PO = axial design load strength of the pile at compression

PT = axial design load strength of the pile in tension

PB = axial design load strength of the pile in simultaneous, assumed, ultimate strain of concrete and yielding of tension reinforcement, balanced conditions

MB = design moment strength of the pile at simultaneous, assumed ultimate strain of concrete and yielding of tension reinforcement, balanced conditions

MO = design moment strength of the pile at zero axial load, pure flexure

$K = 1 - (A/45)(0.15)$

For $M1 \geq M2$, $A = \tan^{-1}(|M2|/|M1|)$

For $M1 < M2$, $A = \tan^{-1}(|M1|/|M2|)$

The SF used in Equations 7, 8, and 9 is equal to 2.7 for hydraulic structures and 2.5 for all other structures. For round or octagonal piles, the biaxial bending capacity equals the uniaxial bending capacity about the principal axis and, therefore, the value of K in Equations 7 through 9 is 1. For biaxial

bending in square piles, the moment capacity is reduced by multiplying the uniaxial bending capacity about the principal axis by a reduction factor K . This relationship is shown in Figure 1 and is valid for square piles with equal reinforcement on all faces (Ramamurthy 1966). Equations 7 through 9 are conservative representations of the actual interaction curves for reinforced and prestressed concrete piles. A plot of interaction Equations 7 through 9,

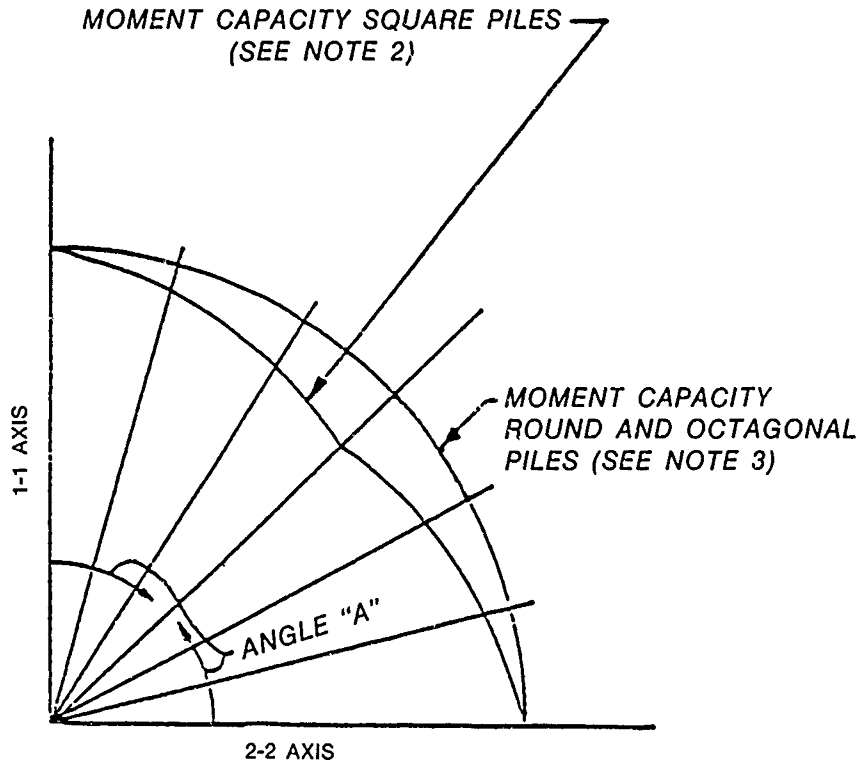


Figure 1. Moment capacity-square, round, and octagonal reinforced or prestressed concrete piles

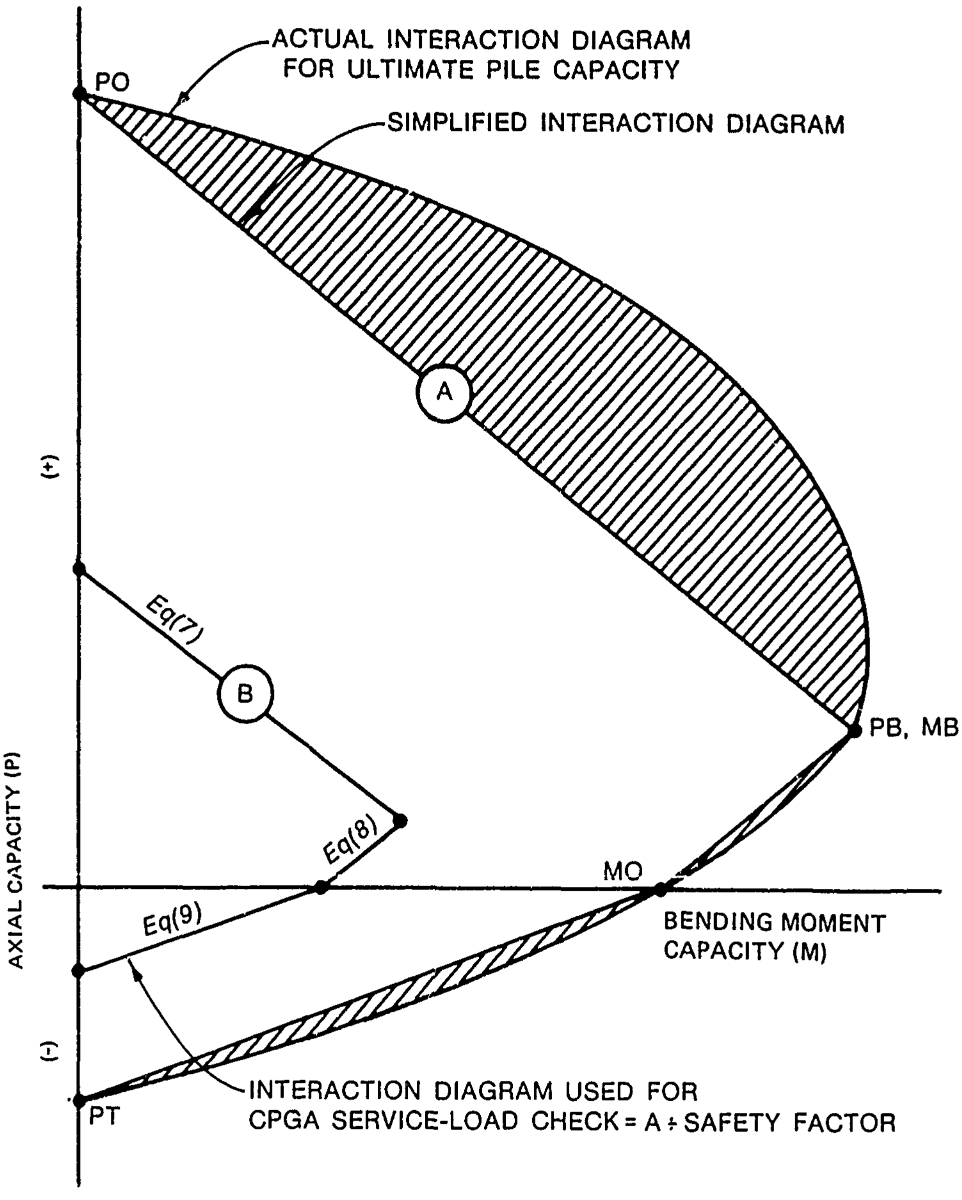
NOTES:

1. Square piles are assumed to be equally reinforced on each face. Moment capacity about 1-1 axis equals the moment capacity about 2-2 axis.

2. For square piles, the moment capacity at an angle "A" to the principal axis is equal to the moment capacity at the principal axis reduced by 0.15 A ÷ 45.

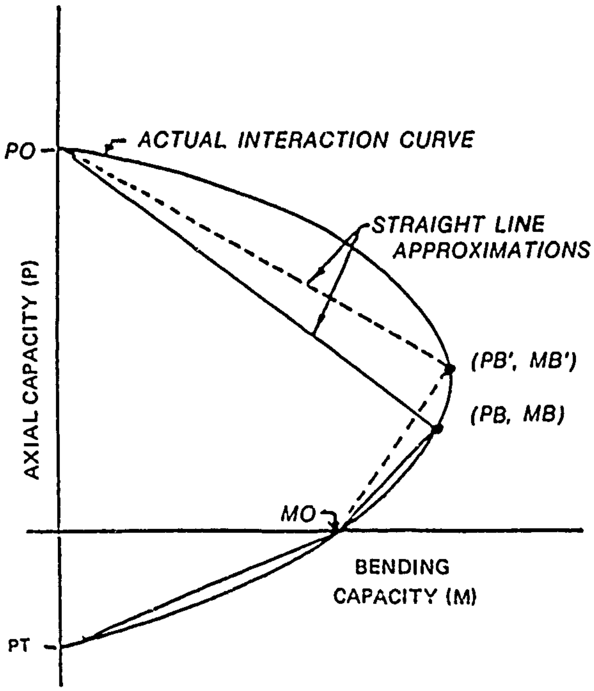
3. For round piles and octagonal piles, the moment capacity at an angle "A" to the principal axis is equal to the moment capacity at the principal axis.

based on the control points PO , PB , MB , MO , and PT is shown in Figure 2. The shaded portion between the actual interaction curve and the simplified straight-line diagram represents the conservatism inherent in the CPGA combined bending and axial load check. When combined bending and axial load factors exceed 1.0, those pile forces should be compared against the actual interaction curves.

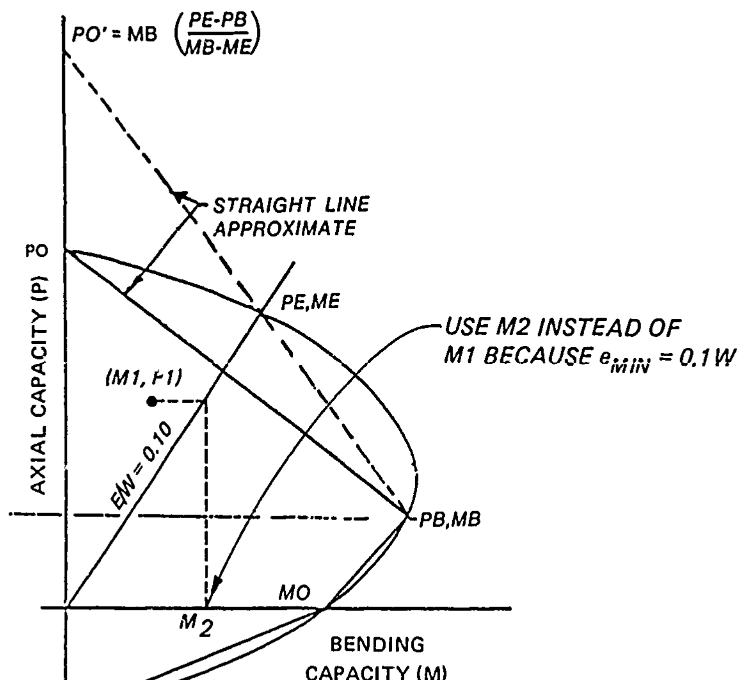


a. Interaction diagram for prestressed and reinforced concrete piles

Figure 2. Plot of interaction equations (Continued)



b. Adjustment of straight-line approximations to interaction curve by movement of balance point



c. Adjustment of straight-line approximations to interaction curve by movement of axial capacity point

Figure 2. (Concluded)

39. In Figure 2a for prestressed concrete piles, the actual balance point may fall well into the portion of the interaction curve where the moment is increasing with axial load. The user may wish to input pseudo values, PB' and MB', for the actual balance axial load and moment so that the straight line approximation is not overly conservative.

40. In Figure 2b, the interaction check is made using a minimum moment equal to the actual axial load, F3, times a minimum eccentricity (Emin), where Emin = 0.10 times the pile width (W). The user may wish to input a pseudo value (PO') for the actual axial design load strength so that the straight-line approximation of the actual interaction curve is not overly conservative. The value of PO' can be determined by direct proportioning methods if the point of intersection between the minimum eccentricity line, M = 0.1W(P), and the actual interaction curve is known.

Implementation of Straight-Line Diagram

41. The simplified straight-line diagram used to develop interaction Equations 7 through 9 is based on the straight-line diagram for ultimate strength reduced by an SF. This SF is constant throughout the entire interaction diagram range whether the strength is controlled by compression or by tension. For hydraulic structures, the SF was conservatively selected assuming a load factor of 1.9 and a strength reduction factor of 0.7 resulting in an SF of 1.9/0.7 or 2.7. For nonhydraulic structures, an SF of 2.5 is used.

42. Prestressed concrete piles are also investigated for combined bending and axial stresses using service-load conditions based on the following equations:

Round or octagonal prestressed concrete piles

Allowable stress check

$$\left[\frac{F3}{A} - \frac{\sqrt{M1^2 + M2^2}}{S}\right]\left(\frac{1}{OSFT}\right) + FPC \geq -FT \qquad (12\ bis)$$

$$\left[\frac{F3}{A} + \frac{(MF1)\sqrt{M1^2 + M2^2}}{S}\right]\left(\frac{1}{OSF}\right) + IPC \leq FA \qquad (13\ bis)$$

Square prestressed concrete piles

Allowable stress check

$$\left[\frac{F3}{A} - \frac{|M1|}{S} - \frac{|M2|}{S}\right]\left(\frac{1}{OSFT}\right) + FPC \geq -FT \qquad (10\ bis)$$

$$\left[\frac{F3}{A} + \frac{(MF1)\,|M1|}{S} + \frac{(MF2)\,|M2|}{S}\right]\left(\frac{1}{OSF}\right) + IPC \leq FA \qquad (11\ bis)$$

where

A = area of pile

S = section modulus of pile about the 1 or 2 axis

FPC = concrete stress due to final prestress force

IPC = concrete stress due to initial prestress force

FA = allowable compressive stress in concrete

FT = allowable tensile stress in concrete

The actual pile stress, represented by the left-hand side of Equations 10 through 13, is output when local pile forces are requested.

Unsupported piles

43. Free-standing piles and fully embedded piles in very weak soil are laterally unsupported for a portion of their length below the pile cap. For unsupported steel and timber piles, the allowable axial loads are a function of the critical buckling load. The moment magnification factors for steel, timber, reinforced, and prestressed concrete piles are also a function of the critical buckling load.

44. For free-standing or partially embedded piles, the critical buckling load can be determined by assuming the piles are fixed some distance below the groundline. The critical buckling load can then be expressed as:

$$PCR = \pi^2\ EI/(KL_T)^2$$

where

E = modulus of elasticity of pile material

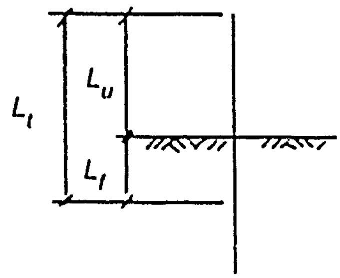
I = moment of inertia of pile

L_T = total unsupported length of pile

= free standing length (L_u) + depth to fixity (L_f)

K = effective length factor

For soils where the subgrade modulus is constant with depth and the free-standing length to relative stiffness factor ratio (Lu/R) is greater than 2.0, the depth to fixity (L_f) is equal to 1.4R. For soils where the subgrade modulus increases linearly with depth and the free-standing length to relative stiffness factor ratio (L_u/T) is greater than 1.0, the depth to fixity (L_f) is equal to 1.8T. This procedure is described in Highway Research Record Number 333.



45. The critical buckling load for partially or fully embedded piles, in soils where the subgrade modulus increases linearly with depth, can be expressed as:

$$PCR = \pi^2 EI\ G_y/T^2$$

where G_y equals the function of the free standing length and the end conditions of a pile cap. A procedure for computing the critical buckling load on this basis can be found in Highway Research Record Number 147.

46. For fully embedded piles in soils with a constant E_s, the critical buckling load can be computed from Hetenyi's "Beams on Elastic Foundation," (1946) as follows:

$$PCR = n\sqrt{E_s EI}$$

where

n = pile head fixity coefficient for a semi-infinite pile (1 = pile head pinned, 2 = pile head fixed)

E_s = stiffness of horizontal subgrade reaction (force per unit length of pile per unit deflection)

EI = pile stiffness defined above

47. For reinforced and prestressed concrete piles, the critical

buckling load is based on the cracked section EI . This can be determined by using ACI 318-77, Equation 10-9 or 10-10 (see ACI for definition of these symbols).

ACI Equation (10-9)
$$EI = \frac{(E_c)\left(\frac{Ig}{5}\right) + (E_s)(I_s)}{(1 + \beta d)}$$

ACI Equation (10-10)
$$EI = \frac{E_c\left(\frac{Ig}{2.5}\right)}{(1 + \beta d)}$$

48. The moment magnification factors can be expressed by the following equations:

$$MF1 = \frac{CM1}{1 - F3\left(\frac{SF}{PCR1}\right)} \geq 1 \quad \text{and} \quad MF2 = \frac{CM2}{1 - F3\left(\frac{SF}{PCR2}\right)} \geq 1$$

or

$$MF = \frac{CM}{1 - F3\left(\frac{SF}{PCR}\right)} \geq 1 \quad \text{for round piles}$$

where

CM1 , CM2 , CM = moment correction factors to account for different end conditions (AISC specifications)

SF = safety factor

49. Other terms have been defined previously. The SF's used in the computation of the moment magnification factor depend on the pile material and structure type (Table 1). The above moment magnification factors are computed for each pile based on its individual axial load and critical buckling load capacity. This procedure is reasonable for piles braced against sidesway (effective unsupported length is equal to or less than the actual unsupported length). It may, however, produce overly conservative moment magnification factors for unbraced piles where the effective unsupported length (KL_T) is greater than the actual unsupported length. This is because sidesway buckling cannot occur unless all piles reach their sidesway buckling capacities.

Table 1

Safety Factors Used to Determine the Moment Magnification Factors for Unsupported Piles

Material	Structure Type	Safety Factor
Steel	Hydraulic	2.15
Timber	Hydraulic	4.80
Concrete	Hydraulic	2.70
Steel	Nonhydraulic	1.92
Timber	Nonhydraulic	4.00
Concrete	Nonhydraulic	2.50

Allowable axial loads and moments

50. The allowable axial loads for fully supported steel and timber piles, ACC and ATT , to be used in interaction Equations 3 through 6 are determined by multiplying the cross-sectional area of the pile by its allowable stress. The allowable stresses for timber and steel piles can be found in Tables A-1 and A-2 of Technical Report K-83-1 (US Army Engineer Waterways Experiment Station 1983), "Basic Pile Group Behavior." For laterally unsupported steel piles, the allowable axial compressive load, ACC , is a function of the critical buckling load, PCR , and can be determined as:

when

$$CC > (\pi^2 EA/PCR)^{0.5}$$

$$ACC = \left[\frac{(Fy)A}{SF}\right]\left[1 - \frac{Fy(A)}{4 \cdot PCR}\right]$$

when

$$CC < (\pi^2 EA/PCR)^{0.5}$$

$$ACC = PCR/SF$$

where

$$CC = (2\pi^2 E/Fy)^{0.5}$$

51. The value of ACC for unsupported steel or timber piles shall not exceed the value of ACC for the fully supported case. The allowable axial load for laterally unsupported timber piles is as follows:

$$ACC = PCR/SF$$

If the critical buckling load is based on the moment of inertia of the pile section at the location where it is considered as supported by the soil, then the critical buckling load may be increased by multiplying that value by the ratio of the diameter of the pile at the pile cap to the diameter of the pile at the location where it is supported by the soil. Again, ACC for unsupported timber piles should not exceed ACC for the fully supported case.

52. The allowable moments for steel and timber piles (AM1, AM2) to be used in interaction Equations 3 through 6 are determined by multiplying the section modulus of the pile by its allowable bending stress. The interaction equations for reinforced and prestressed concrete piles (Equations 7 through 9) are based on design load strengths rather than allowable axial loads and moments. The design load strength can be calculated by the user for given pile cross sections and reinforcement or can be obtained from published interaction curves (Anderson and Moustafa 1970 and PCI Committee 1977).

53. The axial design load compressive strength for reinforced concrete piles based on ACI methods is:

$$PO = 0.85f'_c(Ac - As) + Fy(As)$$

and for prestressed concrete piles based on the PCI Design Handbook (Prestressed Concrete Institute 1980) is:

$$PO = (0.85f'_c - 0.60fpc)Ac$$

54. The axial design load tensile strength for reinforced and prestressed concrete piles is:

$$PT = Fy(As)$$

where

Fy = specified yield strength of reinforcement or prestressing steel

f'_c = specified concrete compressive strength

fpc = concrete stress due to final prestress force

Ac = gross area of pile cross section

As = area of reinforcing or prestressing steel

The design load strengths for PB , MB , and MO can be calculated for a given cross section and reinforcement based on the assumptions given in the ACI (318-83) code or ETL 1110-2-265 (Department of the Army, 1981, "Strength Design Criteria for Reinforced Concrete Hydraulic Structures") and on the satisfaction of the applicable conditions of equilibrium and compatibility of strains.

55. Equations 7 and 8 are valid only if the actual resultant bending moment, $\sqrt{M1^2 + M2^2}$, is greater than F3 × EMIN where EMIN equals the minimum eccentricity. EMIN = 0.10W where W equals the width of a square pile or the diameter of a round pile.

56. The computer program compares the moment based on minimum eccentricity with the actual resultant moment and uses the maximum value in the equations for combined bending and axial load.

57. The pile forces, used for the above comparisons with the allowables, are those forces calculated as acting on the top of the pile. "Pinned" piles, however, have no moment at the top, but do experience bending beneath the top, depending on lateral loads and soil properties. The critical moments may be approximated for design purposes as a constant times the lateral force on the pile

$$M1 = KMP1 \times F2$$

where

M1 = design moment

F2 = lateral force

KMP1 = constant

This may be done for bending about both axes as shown in data input item k, paragraph 24, and these calculated moments are then used in the allowable load

comparisons. When pile and soil properties have been given for a pinned pile, the design moment factors, KMP1 and KMP2 , may be calculated automatically by the program as:

Soil Type	Unsupported Length	KMP1 × F_2	KMP2 × F_1
n_h	0.	$0.772\ T_1F_2$	$-0.772\ T_2F_1$
n_h	L_u	--	--
E_s	0.	$(0.455\ RF_2)$	$-(0.455\ R)F_1$
E_s	L_u	α_1F_2	α_2F_1

where

$$\alpha_1 = \left[\frac{\left(1 + \frac{2L_u}{\sqrt{2}R_1} + \frac{L_u^2}{R_1^2}\right)}{\frac{2}{\sqrt{2}R_1}\left(1 + \frac{L_u^2}{R_1^2} + \frac{2L_u}{\sqrt{2}R_1}\right)^{0.5}}\right] e^{-\tan^{-1}\left(\frac{1}{1 + \frac{2L_u}{\sqrt{2}R_1}}\right)}$$

$$\alpha_2 = \left[\frac{-\left(1 + \frac{2L_u}{\sqrt{2}R_2} + \frac{L_u^2}{R_2^2}\right)}{\frac{2}{\sqrt{2}R_2}\left(1 + \frac{L_u^2}{R_2^2} + \frac{2L_u}{\sqrt{2}R_2}\right)^{0.5}}\right] e^{-\tan^{-1}\left(\frac{1}{1 + \frac{2L_u}{\sqrt{2}R_2}}\right)}$$

where

F1, F2 = pile lateral forces

$T_1 = \sqrt[5]{EI_1/n_h}$ $\quad T_2 = \sqrt[5]{EI_2/n_h}$

$R_1 = \sqrt[4]{EI_1/E_s}$ $\quad R_2 = \sqrt[4]{EI_2/E_s}$

n_h = constant of horizontal subgrade reaction, i.e., the change in E_s with depth (force per unit length of pile per unit deflection per unit depth of soil) (F/L^3)

E_s = stiffness of horizontal subgrade reaction (F/L^2)

E, I = pile properties

L_u = unsupported length

Subscripts 1 and 2 refer to the pile coordinate system axes. For derivation of the above moment factors, refer to "Static and Dynamic Analysis of Pile Foundations," (Saul 1968).

Tension Pile Iteration

58. Piles in tension often have a different axial stiffness than similar piles in compression. The same pile may be in tension for one load case and in compression for others. This means that a pile may have different axial stiffnesses for different loads. However, the basic analysis method of CPGA allows only one value to be specified for the axial stiffness (B_{33}) of a pile. To reduce the inaccuracies caused by the above limitation, CPGA can also perform an iterative solution using a modified stiffness for piles in tension. Immediately after any analysis, the program will list the number of piles in tension for each load case. The user is then asked whether an iterative solution should be performed. If it is requested, the pile layout is reanalyzed one load case at a time. For a given load case, the axial stiffness, B_{33}, of all piles in tension is multiplied by the appropriate tension pile stiffness modifier, CT, to determine a modified axial stiffness, $B_{33}T = CT \times B_{33}$. The pile layout is reanalyzed using the revised pile stiffness. Each pile then has its axial stiffness reset to B_{33} or to $B_{33}T$, depending on whether it is in compression or tension, respectively. This procedure is repeated until two successive analyses produce identical results, or until a maximum of five iterations. If, after five iterations, the results haven't converged, the use is then provided with the following output: the total number of piles that were in tension after each of the five iterations, a list of the piles that have changed sign with respect to their axial force during the last two iterations, and the final pile forces resulting after the fifth iteration. The same procedure is then followed for each load case with piles in tension. During a batch run, if $CT \neq 1$, the program automatically iterates for each load case containing tension piles.

Pile Stiffness

General determinations

59. Lateral, axial, and torsional stiffness must be determined for a

wide range of pile-soil conditions. The pile stiffness is a function of the pile properties (length, pile head fixity, material, area, and moments of inertia), the soil properties (strength, unit weight, stiffness), environmental factors (ground-water table, depositional characteristics, driving methods), and loading conditions (cyclic, group effects, time effects). For complex pile-soil behavior, pile stiffness may be determined by numerical methods using computer programs. Program module CPGS has been developed specifically for this purpose. Details of CPGS capabilities and solution techniques are contained in "Pile Head Stiffness Matrices" (Dawkins 1978). The following paragraphs 60 through 75 present general background information about methods of determining the lateral, axial, and torsional stiffnesses for a single pile.

Pile stiffness definitions

60. Pile stiffness may be represented by a 6 by 6 matrix of stiffness coefficients relating pile head forces to pile head displacements:

$$\{q\} = [b]\{u\}$$

$$\{q\} = \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_6 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} \quad \text{and} \quad \{u\} = \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{Bmatrix} = \begin{Bmatrix} u \\ v \\ w \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{Bmatrix}$$

where q is a set of three forces and three moments, u is a set of three translations and three rotations, and b is the pile stiffness matrix. The stiffness matrix has the following form:

$$[b] = \begin{bmatrix} b_{11} & 0 & 0 & 0 & b_{15} & 0 \\ 0 & b_{22} & 0 & b_{24} & 0 & 0 \\ 0 & 0 & b_{33} & 0 & 0 & 0 \\ 0 & b_{42} & 0 & b_{44} & 0 & 0 \\ b_{51} & 0 & 0 & 0 & b_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{66} \end{bmatrix}$$

where 1 , 2 , and 3 refer to the local pile coordinate system axes and 4 , 5 , and 6 are rotations about those axes, as shown in paragraph 16. The pile stiffness coefficients, are defined as follows:

b_{11}	Force required to displace the pile head a unit distance along the local 1 axis
b_{22}	Force required to displace the pile head a unit distance along the local 2 axis
b_{33}	Force required to displace the pile head a unit distance along the local 3 axis
b_{44}	Moment required to displace the pile head a unit rotation around the local 1 axis
b_{55}	Moment required to displace the pile head a unit rotation around the local 2 axis
b_{66}	Moment required to displace the pile head a unit rotation around the local 3 axis
*b_{15}	Force required along the local 1 axis to resist lateral movement during a unit rotation of the pile head around the local 2 axis
*b_{24}	Force required along the local 2 axis to resist lateral movement during a unit rotation of the pile head around the local 1 axis
*b_{51}	Moment required around the local 2 axis to resist rotation caused by a unit displacement of the pile head along the local 1 axis
*b_{42}	Moment required around the local 1 axis to resist rotation caused by a unit displacement of the pile head along the local 2 axis

Lateral Pile Stiffness

General description

61. The lateral stiffness of a pile is described in terms of shearing forces and moments corresponding to a specified unit translation or rotation of the pile head. There are eight lateral stiffness coefficients, b_{11} , b_{22} , b_{44} , b_{55} , b_{15} , b_{51} , b_{42} , and b_{24} , defined in paragraph 60.

* Since the stiffness matrix must be symmetric, $b_{15} = b_{51}$ and $b_{24} = b_{42}$.

Several methods are available in the literature for determining these stiffness coefficients. The usual practice in the Corps of Engineers (CE) for determining these coefficients is based primarily on research conducted during the last 25 years at the Universities of Texas, Illinois, Oklahoma State, and Houston. The CE approach is an empirical method using the classical beam on elastic foundation theory to model the behavior of a single pile, and representing the actual nonlinear modulus of subgrade reaction by an equivalent elastic secant modulus. The secant modulus used in the analysis is reduced, if needed, to account for the effects of cyclic loading and group interaction with adjacent piles. No correction is made for any differences in lateral stiffness of vertical and batter piles. The following paragraphs present methods usually used for a basic analysis of prismatic piles which are fully or partially embedded in soil. The subgrade modulus may be a constant or may vary linearly with depth.

Fully embedded piles

62. Closed-form solutions are available for uniform cross-sectional piles fully embedded in soil with an E_s which is either constant or varies linearly with depth. When E_s varies with depth, the variation may be represented as

$$E_s = n_h Z$$

where Z is the depth and n_h is the constant of horizontal subgrade reaction. The pile lateral stiffness for these soil conditions is shown in Table 2. The fixity (ability to transfer bending moment) of the pile to the pile cap affects the stiffness of the pile, as indicated by the constant C_0 in Table 2. The constant C_0 has different values for the various stiffness coefficients as shown in Table 3. Derivation of pile stiffness coefficients, bij , is discussed in "Static and Dynamic Analysis of Pile Foundations" (Saul 1968). For derivation of values of pile fixity constants, C_0 , refer to "Pile Head Stiffness Matrices" (Dawkins 1978). These derivations are valid only for fairly long piles, the pile embedded length (L_e) should be greater than 5T or greater than 4R where T and R are defined in Table 2. An internal check is automatically performed for this requirement. If the pile length is less than 5T or 4R , a warning message is printed at the beginning of the output.

Table 2

Pile Stiffness Coefficients

Stiffness Coeff.	Constant E_s	Linear E_s
b_{11}	$C_o EI_2/R_2^3$	$C_o EI_2/T_2^3$
b_{22}	$C_o EI_1/R_1^3$	$C_o EI_1/T_1^3$
b_{44}	$C_o EI_1/R_1$	$C_o EI_1/T_1$
b_{55}	$C_o EI_2/R_2$	$C_o EI_2/T_2$
$b_{15} = b_{51}$	$C_o EI_2/R_2^2$	$C_o EI_2/T_2^2$
$b_{24} = b_{42}$	$-C_o EI_1/R_1^2$	$-C_o EI_1/T_1^2$

where

C_o = pile fixity constant as shown below

$T_1 = \sqrt[5]{EI_1/n_h}$ (in.); $T_2 = \sqrt[5]{EI_2/n_h}$ (in.)

n_h = constant of horizontal subgrade reaction or the change in E_s with depth (lb/in.^{3})

E_s = stiffness of horizontal subgrade reaction (lb/in./in.)

$R_1 = \sqrt[4]{EI_1/E_s}$ (in.); $R_2 = \sqrt[4]{EI_2/E_s}$ (in.)

E = modulus of elasticity of the pile (lb/in.^{2})

I = moment of inertia of the pile (in.^{4})

Subscripts 1 and 2 for I, T, and R refer to the pile coordinate system axes.

Table 3

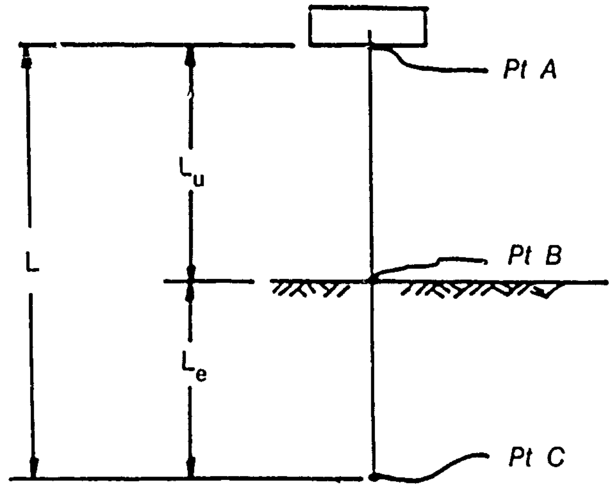
Values of C_o

Stiffness Coeff.	Constant E_s Pile Head Fixity Fixed	Constant E_s Pile Head Fixity Pinned	Linear E_s Pile Head Fixity Fixed	Linear E_s Pile Head Fixity Pinned
b_{11}	1.414	0.707	1.075	0.411
b_{22}	1.414	0.707	1.075	0.411
b_{44}	1.414	0.0	1.5	0.0
b_{55}	1.414	0.0	1.5	0.0
b_{15} & b_{51}	1.0	0.0	1.0	0.0
b_{24} & b_{42}	1.0	0.0	1.0	0.0

Partially embedded piles

63. For certain types of structures such as bridge bents, the base of the structure is well above the groundline and piles must extend above the soil to support the structure. Pile head lateral, axial, and torsional stiffnesses may be significantly affected by that portion of the pile which is unsupported by the soil. For complex pile-soil conditions, the stiffness must be calculated by numerical methods such as in program module CPGS. Reference to this can be found in "Pile Head Stiffness Matrices" (Dawkins 1978). For simpler cases, the lateral stiffness may be determined in a similar manner presented in paragraph 62 for fully embedded piles.

a. A partially embedded pile may be considered as two distinct segments, one segment below the groundline and another segment above. The portion below ground will act as any other fully embedded pile. Therefore, the stiffness of this segment is already known. The portion above ground will act as a beam connecting the structure to the embedded portion of the pile. Stiffness of beams is also a known quantity. Using these known stiffnesses, for a beam and a fully embedded pile, the lateral, axial, and torsional stiffnesses of a partially embedded pile may be determined. The unsupported segment of the pile extends downward from the pile head, point A, to the groundline, point B. The embedded portion of the pile extends downward from point B to the pile tip, point C.



The stiffness of the unsupported segment can be represented by the following matrix, "Basic Pile Group Behavior," Technical Report K-83-1, (Department of the Army 1983):

$$
[M_{ij}] = \begin{bmatrix}
M_{11} & & & & & & & & & & & \\
0 & M_{22} & & & & & & & & & & \\
0 & 0 & M_{33} & & & & & & & & & \\
0 & M_{42} & 0 & M_{44} & & & & & & \text{SYMMETRIC} & & \\
M_{51} & 0 & 0 & 0 & M_{55} & & & & & & & \\
0 & 0 & 0 & 0 & 0 & M_{66} & & & & & & \\
M_{71} & 0 & 0 & 0 & M_{75} & 0 & M_{77} & & & & & \\
0 & M_{82} & 0 & M_{84} & 0 & 0 & 0 & M_{88} & & & & \\
0 & 0 & M_{93} & 0 & 0 & 0 & 0 & 0 & M_{99} & & & \\
0 & M_{10,2} & 0 & M_{10,4} & 0 & 0 & 0 & M_{10,8} & 0 & M_{10,10} & & \\
M_{11,1} & 0 & 0 & 0 & M_{11,5} & 0 & M_{11,7} & 0 & 0 & 0 & M_{11,11} & \\
0 & 0 & 0 & 0 & 0 & M_{12,6} & 0 & 0 & 0 & 0 & 0 & M_{12,12}
\end{bmatrix}
$$

where subscripts, 1 through 6, refer to the 6 degrees of freedom (DoF) at point A in the pile coordinate system, and subscripts 7 through 12 refer to the 6 DoF at point B. A pile which is fixed (transfers moment) to the pile cap has the following values in the above matrix.

$$M_{11} = M_{77} = -M_{71} = 12EI_2/L_u^3$$

$$M_{22} = M_{88} = -M_{82} = 12EI_1/L_u^3$$

$$M_{33} = M_{99} = -M_{93} = AE/L_u$$

$$M_{44} = M_{10,10} = 4EI_1/L_u$$

$$M_{55} = M_{11,11} = 4EI_2/L_u$$

$$M_{66} = M_{12,12} = -M_{12,6} = GJ/L_u$$

$$M_{10,4} = 2EI_1/L_u$$

$$M_{11,5} = 2EI_2/L_u$$

$$M_{51} = M_{11,1} = -M_{75} = -M_{11,7} = 6EI_2/L_u^2$$

$$M_{42} = M_{10,2} = -M_{84} = -M_{10,8} = -6EI_1/L_u^2$$

where A , E , I , G , and J are the usual material and cross-sectional properties, and L is the length of the unsupported segment.

A pile which is pinned (does not transfer moment) to the pile cap has the following values in the matrix:

$$M_{11} = M_{77} = -M_{71} = 3EI_2/L_u^3$$

$$M_{22} = M_{88} = -M_{82} = 3EI_1/L_u^3$$

$$M_{33} = M_{99} = -M_{93} = AE/L_u$$

$$M_{44} = M_{42} = M_{84} = M_{10,4} = 0$$

$$M_{55} = M_{51} = M_{75} = M_{11,5} = 0$$

$$M_{66} = M_{12,12} = -M_{12,6} = GJ/L_u$$

$$M_{10,10} = 3EI_1/L_u$$

$$M_{11,11} = 3EI_2/L_u$$

$$M_{11,1} = -M_{11,7} = 3EI_2/L_u^2$$

$$M_{10,2} = -M_{10,8} = -3EI_1/L_u^2$$

b. The stiffness matrix of the unsupported segment may be partitioned into quadrants

$$[M_{ij}] = \begin{bmatrix} [M_{AA}] & [M_{AB}] \\ [M_{BA}] & [M_{BB}] \end{bmatrix}$$

where the subscripts refer to points A and B. Similarly, the stiffness of the embedded portion may be represented by the partitioned matrix

$$[N_{ij}] = \begin{bmatrix} [N_{BB}] & [N_{BC}] \\ \\ [N_{CB}] & [N_{CC}] \end{bmatrix}$$

where the subscripts refer to points B and C. The quadrant N_{BB} consists of the stiffness coefficients for the fully embedded pile. The other three quadrants are immaterial, since point C represents a fixed point. The assembled stiffness matrix for the entire pile then becomes

$$[K] = \begin{bmatrix} [M_{AA}] & [M_{AB}] & [0] \\ [M_{BA}] & [M_{BB} + N_{BB}] & [N_{BC}] \\ [0] & [N_{CB}] & [N_{CC}] \end{bmatrix}$$

and by deleting the rows and columns relating to fixed point C it simplifies

$$[K] = \begin{bmatrix} [M_{AA}] & [M_{AB}] \\ \\ [M_{BA}] & [M_{BB} + N_{BB}] \end{bmatrix}$$

this stiffness matrix can be used in the following equation

$$\begin{Bmatrix} \{q_A\} \\ \\ \{q_B\} \end{Bmatrix} = [K] \begin{Bmatrix} \{U_A\} \\ \\ \{U_B\} \end{Bmatrix}$$

or

$$\{q\} = [K]\{u\}$$

where q is the set of forces and u is the set of displacements at points A and B, as denoted by the subscripts. The

matrix equation can be written as a set of two simultaneous equations

$$\{q_A\} = [M_{AA}]\{U_A\} + [M_{AB}]\{U_B\}$$

$$\{q_B\} = [M_{BA}]\{U_A\} + [M_{BB} + N_{BB}]\{U_B\}$$

c. Since loads are applied to the pile only at the pile head, point A, then $\{q_B\} = 0$. Therefore,

$$0 = [M_{BA}]\{U_A\} + [M_{BB} + N_{BB}]\{U_B\}$$

$$\{U_B\} = -[M_{BB} + N_{BB}]^{-1} [M_{BA}]\{U_A\}$$

Substituting this equation into the previous equation for q_A gives

$$\{q_A\} = [M_{AA}]\{U_A\} - [M_{AB}][M_{BB} + N_{BB}]^{-1} [M_{BA}]\{U_A\}$$

$$\{q_A\} = [[M_{AA}] - [M_{AB}][M_{BB} + N_{BB}]^{-1} [M_{BA}]]\{U_A\}$$

which is another form of the individual pile stiffness equation

$$\{q\} = [b]\{u\}$$

since $\{q_A\}$ represents pile-head forces and $\{U_A\}$ represents pile-head displacements. Therefore, the pile stiffness matrix for a partially embedded pile is

$$[b] = [M_{AA}] - [M_{AB}][M_{BB} + N_{BB}]^{-1}[M_{BA}]$$

where

$[N_{BB}]$ = stiffness of the fully embedded portion

$[M_{AA}]$, $[M_{AB}]$, $[M_{BB}]$, $[M_{BA}]$ = quadrants of the stiffness matrix for the unsupported length

The axial stiffness for the unsupported height is calculated as AE/L_u. The axial stiffness modifier for the embedded portion is calculated as discussed in paragraph 64. The axial stiffness modifier for the embedded portion is read into the program via input data item b, paragraph 24. Input data item j, paragraph 24 may also be used to modify the embedded portion axial stiffness for any piles in tension. The axial stiffness for the unsupported length (L_u) is automatically combined with the axial stiffness for the embedded portion of the pile (L_e) within the program. Pile torsional stiffness is specified for the total pile length (L_t) (embedded length (L_e) and unsupported length (L_u) and is read into the program via input data items b and e, paragraph 24 as discussed in paragraph 64.

Axial Pile Stiffness

General definition

64. The axial stiffness of a pile is defined as the axial force required to displace the pile top a unit distance in the axial direction. Several methods are available for determining axial pile stiffness. These methods are classified generally as elasticity solutions (Poulos and Davis 1980, Randolph and Wroth 1978) or as empirical approach (Dawkins 1984, Radhakrishnan and Parker 1975, Vesic 1977, Scott 1981). The Corps of Engineers (CE) approach accounts for pile-soil interaction effects by applying an empirical factor (C_{33}) to the stiffness coefficient (AE/L_e) of an axially loaded structural member. This approach is valid only if the selection of the empirical factor is correlated with available geotechnical data for the project site, and with the results of load tests and engineering experience from previous projects. Stiffness coefficients for compression and tension piles will be discussed separately because their load transfer mechanisms are different. Therefore, the stiffness coefficients will not be equal for identical piles which are equally loaded in tension or compression.

CE compression pile axial stiffness

65. Axial load in a compression pile is transferred to the soil by a combination of tip bearing and skin friction. Basic design practice in the CE is to estimate the axial stiffness coefficient by applying an empirical factor C_{33} to AE/L_e of an axially loaded structural member, as is shown in Figure 3.

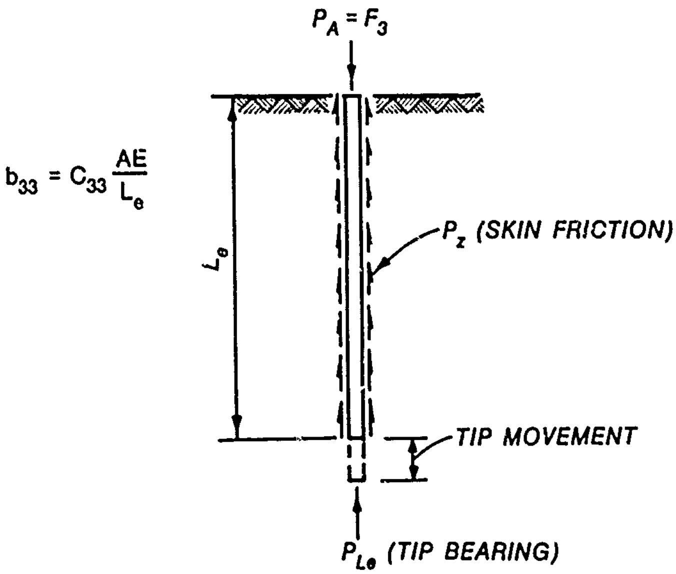
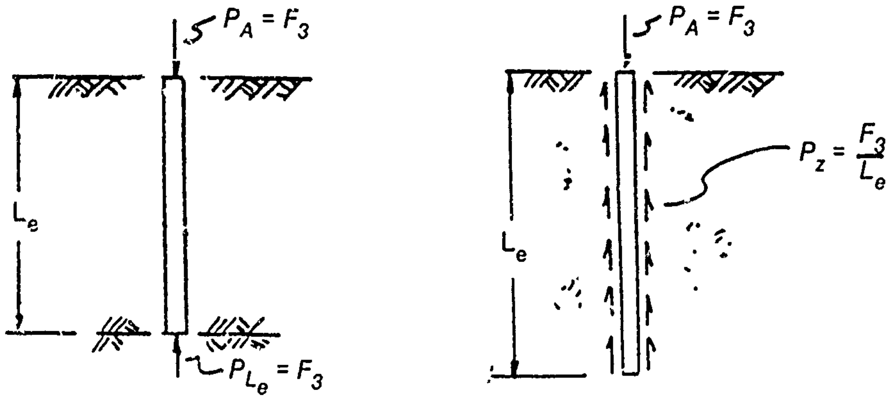


Figure 3. Load transfer by combined skin friction and tip bearing for an axially loaded compression pile

An axial stiffness coefficient of AE/L_e represents an ideal pile which transfers all its load by tip bearing, as shown in Figure 4a. Similarly, an axial stiffness coefficient of $2AE/L_e$ represents an ideal pile which transfers all its load by skin friction uniformly along its length with no tip movement, as seen in Figure 4b. The load-deflection curve for compression piles is essentially linear to one half the ultimate pile capacity (the design load) as shown in Figure 5, so nonlinearity of the axial load-deflection curve can be neglected and axial pile stiffness can be determined by using an



a. Full tip bearing $C_{33} = 1$

b. Full skin friction $C_{33} = 2$

Figure 4. Load transfers for an axially loaded compression pile

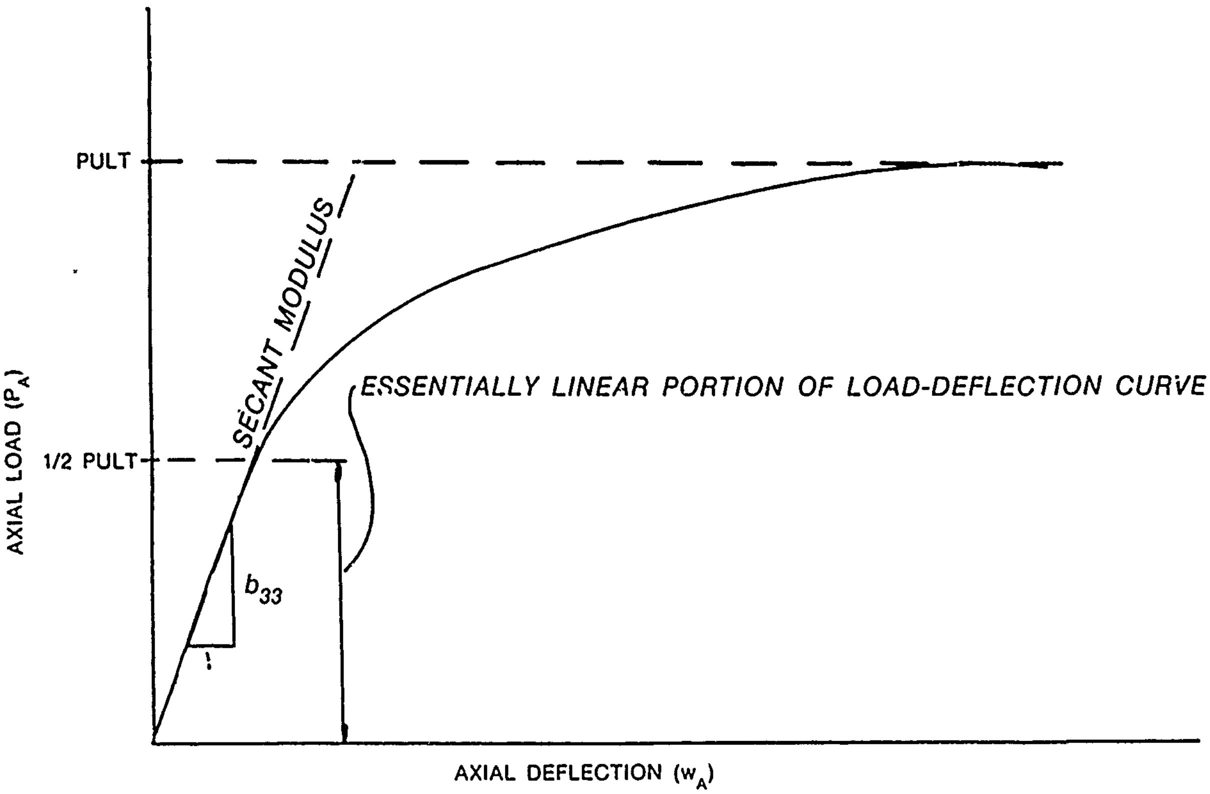


Figure 5. Pile axial load-deflection curve

equivalent secant modulus. In computer program CPGA, the axial pile stiffness is formulated as:

$$b_{33} = C_{33}(AE/L_e) \tag{14}$$

where

b_{33} = axial pile stiffness

C_{33} = axial stiffness modifier which accounts for the interaction between the soil and the pile

A = cross-sectional area of the pile

E = modulus of elasticity of the pile

L_e = embedded length of the pile

As shown in Figure 5, b_{33} is the slope of the secant modulus. The slope of the secant modulus b_{33} can be represented as:

$$b_{33} = P_A/w_A \tag{15}$$

where

P_A and w_A = points on the pile load-deflection curve through which the secant modulus passes

P_A = axial load applied to the pile at the ground surface

w_A = axial deflection of the pile at the ground surface

Combining Equations 14 and 15 gives:

$$P_A/w_A = C_{33}(AE/L_e) \tag{16}$$

The deflection of an axially loaded column with no soil present is:

$$\Delta = PL_e/AE \tag{17}$$

where Δ is the deflection of the column top. Combining Equations 16 and 17 and solving for C_{33} gives:

$$C_{33} = \Delta/w_A \tag{18}$$

Thus, the axial pile stiffness modifier is the theoretical deflection of an equivalent column with the same properties as the pile (i.e., length, cross-sectional area, modulus of elasticity) divided by the deflection of the pile due to the same load level.

66. The w_A of an axially loaded pile in compression can be determined by any of many different methods. Once the axial pile deflection (settlement) is obtained, the axial pile stiffness modifier for piles in compression can be calculated by using Equation 18. It is suggested that C_{33} fall within the range of 0.5 to 2.0 for compression piles. The following are a few methods for calculating pile deflection:

<u>a</u>. <u>Pile load test.</u> The load-deflection curve from a pile load test can be used to determine pile deflection. A pile load test performed at the site is the most accurate method for determining axial deflection at the top of the pile. Pile load tests at sites with similar geologic conditions and similar pile types can be used to determine pile axial deflection.

<u>b</u>. <u>Load transfer analysis.</u> Many computer programs exist for calculating the load-deflection curve for compression piles using the t-z curve method of analysis (Coyle and Reese 1966, Coyle and Sulaiman 1967, Vijayrergiya 1977, Kraft, Focht, and Amerasinghe 1981, and Mosher 1984). Two such programs available to Corps users are CAXPILE and PX4C3 (Dawkins 1984, Radhakrishnan and Parker 1975).

c. Vesic's method. Vesic (1977) has developed an empirical method for calculating the axial deflection of a pile for load levels up to the design load. This method is applicable for both driven and bored piles and is extremely easy to use.

d. Poulos' method. Poulos (1980) has developed a method for calculating pile deflection based on theory of elasticity solutions.

e. Other methods. Many other methods are available in the literature for calculating axial pile deflections. A few of these methods are Randolph's method (1978), Scott's method (1981), finite element methods, etc. Any method for calculating pile settlement can be used to calculate the axial pile stiffness modifier Equation 18, and the axial pile stiffness, Equation 14.

Other factors affecting pile deflection and, thus, the axial stiffness are cyclic loading, group effects, and time.

(1) Cyclic loading. Cyclic loading of a pile would tend to increase the settlement of a pile thus decrease the axial stiffness. At present, the effect of cyclic loading on axial stiffness is neglected.

(2) Group effects. When piles are arranged in a closely spaced group, the stress bulbs caused by the loaded piles tend to overlap. Overlapping stress bulbs load the same volume of soil causing more settlement of a pile, thus reducing the stiffness. In design for piles driven to refusal in sand, or to a hard layer, no decrease in axial stiffness is made to account for group effects. To account for group effects, where necessary, the settlement of the group of piles should be calculated and Equation 18 used to calculate the axial stiffness modifier of the pile group. Settlement of a group of piles can be calculated by using the equivalent pier method (Meyerhof 1976) or group settlement factors (Vesic 1977).

(3) Time. In sand, long-term loading has little effect on the axial stiffness; however, consolidation in clay due to long-term loading reduces the axial stiffness. In sand, most settlement occurs immediately; however, there continues to be a small amount of settlement at a rate which decreases with time. This continuing settlement may be estimated using simple empirical relationships (Duncan and Buchignani 1976), but is usually neglected in calculating axial pile stiffness. In clay, some settlement occurs immediately. This initial, immediate settlement is followed by settlement due to consolidation and later secondary compression which can take place for long periods of time. Limited field observations indicate that only immediate settlement need be considered when calculating the axial stiffness of piles in clay with an undrained shear strength greater than 2,000 psf. For piles in clay with undrained shear strength less than 2,000 psf, settlement

due to consolidation may need to be taken into account when calculating axial pile stiffness.

Tension pile axial stiffness

67. For piles in tension, the axial stiffness modifier can be obtained by using Equation 18; however, the axial deflection, w_A , of piles in tension is not readily calculated. Certainly, axial deflection of tension piles can be obtained from pile load tests, but most of the other methods are not applicable for tension piles. For this reason, the axial stiffness of tension piles in sand is usually taken as one half the compression stiffness for that pile. For piles in clay, the axial stiffness modifier of tension piles is usually 75 to 80 percent of that for compression piles.

Proposed CE alternate method

68. As stated in paragraph 65 and shown in Figure 5, the load-deflection curve for an axially loaded pile is essentially linear to one half of the ultimate pile capacity. This observation leads to the conclusion that the pile-soil response (for design loads) can be modeled as a column on elastic axial supports. This model is analogous to the beam on elastic foundation model used for determining the lateral stiffness coefficients (paragraph 61). Such a model would be useful because it would provide information about the variations of pile displacements, skin friction resistance, and axial force along the pile length. This model would also provide an alternative approach to compute solutions like CPGS for preliminary designs or for simple foundation conditions similar to the equations in paragraph 62 and for lateral loading effects.

69. Development of this alternative approach is in progress at Oklahoma State University and the University of Houston. The major research effort is aimed at developing guidance to evaluate the axial modulus of subgrade reaction for constant or linear variations in modulus with depth. Experimental and analytical results indicate that the rate of load transfer increases with depth below ground surface, and except for very short, rigid piles, the axial displacement of the pile diminishes rapidly with depth.

70. Load-transfer versus displacement curves were derived from experimental data under the implicit assumption that load transfer at any point is a function of the pile displacement at that point only. A typical curve for skin friction is shown in Figure 6. In an iterative solution, repeated adjustments in displacement are made until equilibrium and force-displacement

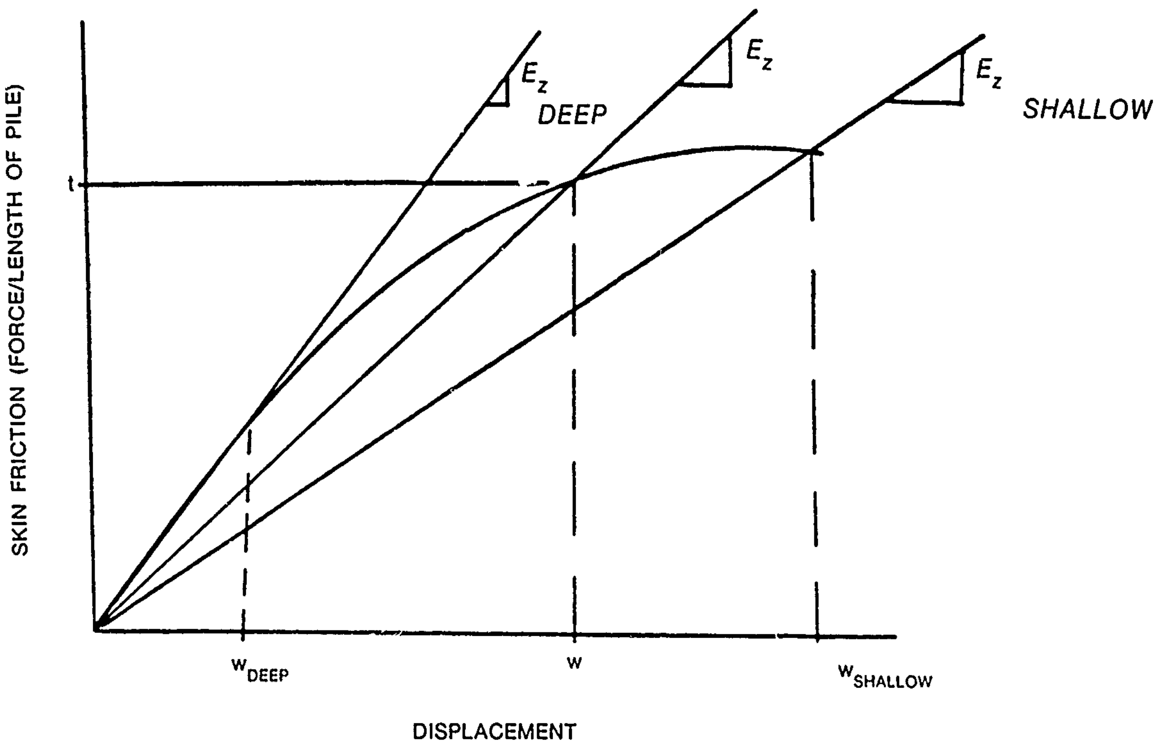


Figure 6. Typical axial load-transfer curve

compatibility are attained at every point along the pile. An approximate solution can be obtained if the nonlinear load-transfer curves are replaced at every point along the pile by a linearly elastic resistance which has a stiffness (E_z) as shown in Figure 6. With the observation that displacements are largest near the ground surface and diminish with depth, it can be concluded that the effective stiffness of the load-transfer mechanism is low near the ground surface and increases with increasing depth (e.g., $E_{z\ shallow}$ and $E_{z\ deep}$, in Figure 6).

71. Since the pile itself is presumed to remain linearly elastic, the above observations imply that the pile-soil response may be obtained from an analysis of a linearly elastic pile-soil system in which the stiffness of the soil varies with depth. Using the pile soil system in Figure 7a, the analysis of the typical element shown in Figure 7b requires

$$dP_z = -EA \frac{dw}{dz} \tag{19}$$

$$\frac{d}{dz}\left[EA\frac{dw}{dz} - E_z\ wdz\right] = 0 \qquad (20)$$

where

E = modulus of elasticity of pile

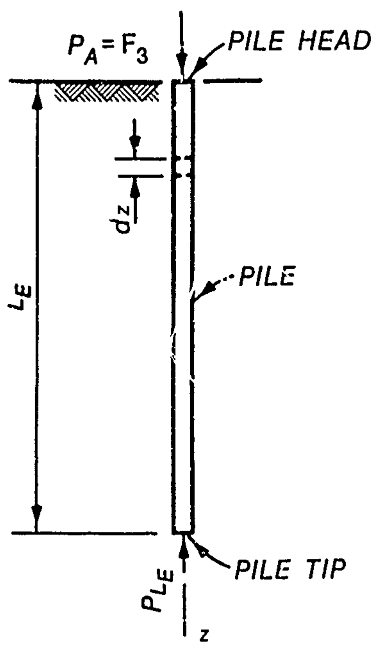
A = cross-sectional area of pile

w = pile axial displacement

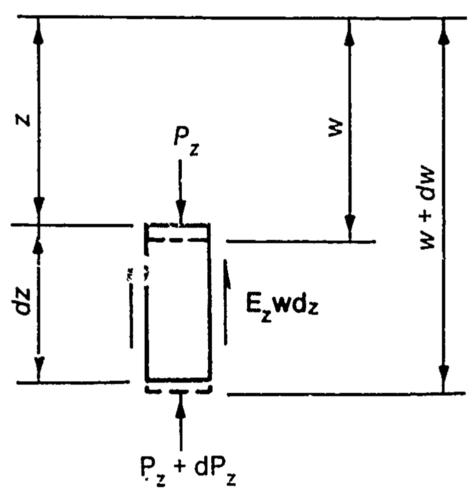
E_z = stiffness of the skin friction reaction

P_z = axial compressive force in pile

Closed-form solutions of Equations 19 and 20 are possible only if E , A , and E_z are constant. Explicit solutions of this special case are presented below.



a. System



b. Typical element

Figure 7. Linearly elastic pile-soil system subjected to axial load

For E , A , and E_z , all constants (i.e., prismatic pile with constant soil modulus), Equation 20 reduces to

$$EA\frac{d^2w}{dz^2} - E_z w = 0 \qquad (21)$$

and its solutions

$$w = C_1 \cosh \frac{z}{R_3} + C_2 \sinh \frac{z}{R_3} \tag{22}$$

$$P_z = - \frac{EA}{R_3} C_1 \sinh \frac{z}{R_3} + C_2 \cosh \frac{z}{R_3} \tag{23}$$

where $R_3 = EA/E_z$, C_1 , and C_2 are constants to be determined from conditions at the pile head (z = 0) and the pile tip ($z = L_E$). At the pile head, $P_z = P_A = F_3$, whence

$$C_2 = - \frac{F_3 R_3}{EA} \tag{24}$$

At the pile tip, $P_z = P_{L_E}$, three alternative conditions are presented: Tip reaction equal zero: At $z = L_E$, $P_{L_E} = 0$, hence

$$C_1 = \frac{F_3 R_3}{EA} \frac{\cosh \frac{L_E}{R_3}}{\sinh \frac{L_E}{R_3}}$$

and

$$w = \frac{F_3 R_3}{EA} \left(\frac{\cosh \frac{L_E}{R_3}}{\sinh \frac{L_E}{R_3}} \cosh \frac{z}{R_3} - \sinh \frac{z}{R_3} \right) \tag{25}$$

$$P_z = F_3 \left(\cosh \frac{z}{R_3} - \frac{\cosh \frac{L_E}{R_3}}{\sinh \frac{L_E}{R_3}} \sinh \frac{z}{R_3} \right) \tag{26}$$

Tip displacement equal zero: at $z = L_E$, $w = 0$, hence

$$C_1 = \frac{F_z R_3}{EA} \frac{\sinh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3}}$$

and

$$w = \frac{F_3 R_3}{EA} \left(\frac{\sinh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3}} \cosh \frac{z}{R_3} - \sinh \frac{z}{R_3} \right) \tag{27}$$

$$P_z = F_3 \left(\cosh \frac{z}{R_3} - \frac{\sinh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3}} \sinh \frac{z}{R_3} \right) \tag{28}$$

Tip elastically restrained with tip reaction equal to $E_z w$. At $z = L_E$, $P_{L_E} = E_z w$

$$C_1 = \frac{F_3 R_3}{EA} \left(\frac{\sinh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \cosh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3} + \frac{EA}{E_2 R_3} \sinh \frac{L_E}{R_3}} \right)$$

and

$$w = \frac{F_3 R_3}{EA} \left(\frac{\sinh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \cosh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \sinh \frac{L_E}{R_3}} \cosh \frac{z}{R_3} - \sinh \frac{z}{R_3} \right) \tag{29}$$

$$P_z = F_3 \left(\cosh \frac{z}{R_3} - \frac{\sinh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \cosh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \sinh \frac{z}{R_3}} \sinh \frac{z}{R_3} \right) \tag{30}$$

72. Of particular interest is the relationship between the pile head force (F_3) and the pile head displacement (w). This relationship is defined by Equations 25, 27, or 29 for $z = 0$ as

$$w = \frac{F_3 R_3}{EA} a_o \tag{31}$$

where

a. Pile tip free

$$a_o = \frac{\cosh \frac{L_E}{R_3}}{\sinh \frac{L_E}{R_3}}$$

b. Pile tip fixed

$$a_o = \frac{\sinh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3}}$$

c. Pile tip elastically restrained

$$a_o = \frac{\sinh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \cosh \frac{L_E}{R_3}}{\cosh \frac{L_E}{R_3} + \frac{EA}{E_z R_3} \sinh \frac{L_E}{R_3}}$$

It is observed for fully embedded piles that for values of L_E/R_3 greater than 2, conditions at the top have negligible effect on the pile head force-displacement relationship. The pile head stiffness coefficient is obtained from

$$b_{33} = \frac{F_3}{w} = \left(\frac{EA}{R_3}\frac{1}{a_o}\right)\left(\frac{L_E}{L_E}\right) = \left(\frac{L_E}{a_o R_3}\right)\frac{EA}{L_E} = C_{33}\frac{EA}{L_E} \tag{32}$$

$$C_{33} = \frac{L_E}{a_o R_3} \tag{33}$$

Torsional Pile Stiffness

73. The torsional pile stiffness is expressed as:

$$b_{66} = C_{66}\frac{JG}{(L_e + C_{66}L_u)}$$

where

b_{66} = the torsional pile stiffness

C_{66} = a constant which accounts for the interaction between the soil and the pile

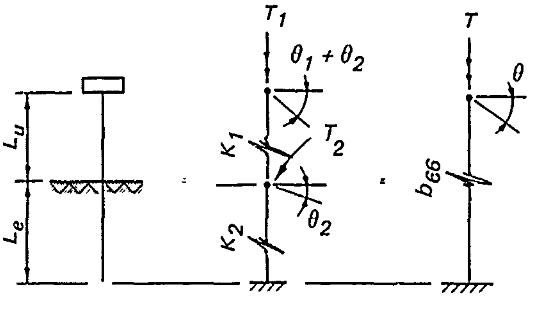
J = the polar moment of inertia of the pile

G = the shear modulus of the pile

L_e = the embedded length of the pile

L_u = the unsupported length of the pile

This is derived for the general case of an unsupported pile as follows:



$T_1 = T_2 = T$

$\theta_1 + \theta_2 = \theta$

$T_1 = K_1\theta_1$

$T_2 = K_2\theta_2$

$T = b_{66}\theta$

where

$$b_{66} = \frac{K_1 K_2}{K_1 + K_2}$$

Substituting

$$K_1 = \frac{JG}{L_u} \qquad \text{and} \qquad K_2 = C_{66} \frac{JG}{L_e}$$

$$b_{66} = \frac{\frac{JG}{L_u} C_{66} \frac{JG}{L_e}}{\frac{JG}{L_u} + C_{66} \frac{JG}{L_e}}$$

$$b_{66} = \frac{C_{66} GJ}{(L_e + C_{66} L_u)}$$

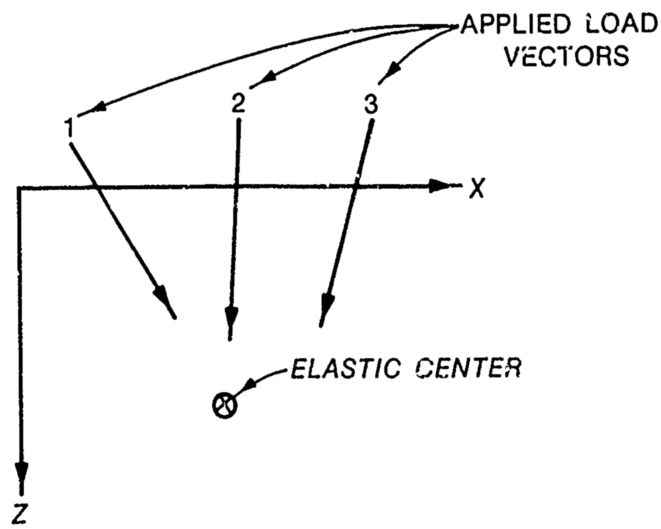
74. The torsional pile stiffness appears to contribute little to the stiffness of a pile group and in the past has been taken as zero. A more reasonable torsional stiffness can be obtained by using $C_{66} = 2.0$. $C_{66} = 0.0$ is correct for cases where the piles are not torsionally fixed into the pile cap, thus transfer no torque to the pile cap. For designs where torsional pile stiffness appears to be critical, the following references may be consulted (O'Neill 1964, Stoll 1972, and Scott 1981).

75. Development of an alternate CE approach is in progress. The major effort is aimed at developing a torsional model analogous to the lateral stiffness model using beam on elastic foundation theory. Such a model will provide a consistency between all the modes of pile behavior.

Elastic Center

76. Foundation piles transmit loads from the superstructure into the soil. It is generally more desirable to develop a pile layout such that each pile transfers an equal load to the foundation. Pile loads will be uniform when applied loads cause only translational movement (vertical and horizontal)

of the pile cap, with no rotational or overturning movement. For a given pile foundation, applied loads along certain lines of action will cause no rotation of the pile cap. The intersection of two such lines of action is called an "elastic center." An applied load in any direction and acting through the elastic center will cause no rotation of the pile cap. To develop an efficient pile foundation, the engineer should ensure that the elastic center of the pile group falls close to the lines of action of the various applied loads.



The position of the elastic center can be moved by manipulating pile group parameters such as pile location, batter, batter direction, angle, etc. The position of the elastic centers is determined from the pile group stiffness matrix as calculated by the program. For a 2-D analysis in the XZ plane, the elastic center has coordinates ECX , ECZ . The value of these coordinates can be determined as follows from the basic equations for behavior of the pile group.

$$\{Q\} = [K]\{U\}$$
$$\{U\} = [H]\{P\}$$

where

Q = set of applied loads

U = set of pile cap displacements

K = pile group stiffness matrix

H = pile group flexibility matrix, the inverse of K

Limiting the second equation to the three DoF associated with the XZ plane gives

$$\begin{Bmatrix} D_x \\ D_z \\ R_y \end{Bmatrix} = \begin{bmatrix} H_{xx} & H_{xz} & H_{xy} \\ H_{zx} & H_{zz} & H_{zy} \\ H_{yx} & H_{yz} & H_{yy} \end{bmatrix} \begin{Bmatrix} P_x \\ P_z \\ M_y \end{Bmatrix}$$

where the subscripts X , Z , Y refer to the X and Z directions and the rotation about the Y axis. For a force through the elastic center, $R_Y = 0$. Therefore,

$$R_y = H_{yx}P_x + H_{yz}P_z + H_{yy}M_y = 0$$

For a force parallel to the Z axis, i.e. $P_x = 0$,

$$0 = H_{yz}P_z + H_{yy}M_y$$

which can also be written as

$$\frac{-M_y}{P_z} = \frac{H_{yz}}{H_{yy}}$$

and since $-M_y/P_z$ defines the X coordinate of the line of action of the force, this identifies the X location of the elastic center:

$$ECX = \frac{-M_y}{P_z} = \frac{H_{yz}}{H_{yy}}$$

Similarly, the Z coordinate of the elastic center may be found to be

$$ECZ = \frac{M_y}{P_z} = \frac{-H_{yz}}{H_{yy}}$$

Note that the elastic center location is independent of applied loads; it is

determined only from the flexibility matrix terms. In the above equations, the loads are defined as those acting through the elastic center. The elastic center coordinates for the YZ plane can be derived in a similar manner. The set of elastic center coordinates for the YZ plane are:

$$ECY = \frac{-H_{xz}}{H_{xx}}$$

$$ECZ = \frac{H_{xy}}{H_{xx}}$$

Frequently, pile group behavior is three-dimensional (3-D) with simultaneous motions for all six DoF. For these conditions, an elastic center cannot be correctly defined as a specific point in a given plane. This is due to the complications presented by the presence of the nonzero off-diagonal terms in the flexibility matrix. The program calculates the elastic center location for 2-D problems. These locations are included in the pile group stiffness matrix output set.

Specified Pile Cap Displacements

77. The basic matrix equation to be solved by CPGA is:

$$\{Q\} = [K]\{U\}$$

where

$$\{Q\} = \begin{Bmatrix} P_x \\ P_y \\ P_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} \quad \text{and} \quad \{U\} = \begin{Bmatrix} D_x \\ D_y \\ D_z \\ R_x \\ R_y \\ R_z \end{Bmatrix}$$

where

$\{Q\}$ = set of applied loads

$\{U\}$ = set of displacements

$[K]$ = 6 × 6 stiffness matrix for the entire pile group

Since displacements are usually the unknowns, the solution has the form:

$$\{U\} = [H]\{Q\}$$

where the stiffness matrix $[K]$ has been inverted to form $[H]$, or $[K]^{-1} = [H]$. When a certain displacement is specified as part of the input, the solution method is modified slightly. Consider the basic matrix equation as a set of six simultaneous equations:

$$Q_i = \sum_{j=1}^{6} H_{ij}U_j \qquad i = 1, 6$$

When a certain displacement is specified, that displacement is multiplied by the appropriate stiffness term and moved to the left of the equation, forming a modified load set. For example, if U_1 was specified, the new equation for load Q_3 would be:

$$Q_3' = Q_3 - H_{31}U_1 = \sum_{j=2}^{6} H_{3j}U_j$$

This modification is performed for each load and for each specified displacement. The terms in the load and displacement vectors, and in the stiffness matrix, which correspond to the specified displacements, are then partitioned out of the basic matrix equation. The solution then takes the form:

$$\{U'\} = [H'][Q]$$

and

$$\{U\} = \begin{Bmatrix} \{U'\} \\ \\ \{U_s\} \end{Bmatrix}$$

where the primes indicate the remainders of the vectors and matrix after partitioning, and U_s is the set of specified displacements. Note that if U_i is specified, the input value of Q_i required to produce the specified displacement can be calculated as follows:

$$Q_i = \sum_{j=1}^{6} H_{ij} U_j \qquad i = 1, 6$$

where U_j is the set of pile cap displacements calculated by the program or specified by the user.

Stability of Two-Dimensional Pinned Pile Layouts

78. Two-dimensional layouts of pinned piles have a potential for being unstable. If all pile heads are colinear and the piles have zero rotational stiffness, there is no stiffness to prevent potential rotation of the pile cap about the line through the pile heads. Even if no load is applied to cause such rotation, this condition would cause an error in the normal solution procedure in CPGA. This problem may occur when analyzing a typical 2-D strip of a real 3-D structure. To facilitate solution of a problem of this type, CPGA will automatically prevent certain instabilities. When an instability exists because all piles are pinned and aligned along the global X or Y axis, the pile group stiffness matrix has a zero value for the B_{44} or B_{55} term. CPGA will check these terms, and if either is zero, it will perform only a 2-D analysis. If B_{44} (rotational stiffness about the global X axis) is zero, the problem will be treated as 2-D in the XZ plane; Y deflection and X and Z rotation will bet set to zero. CPGA will then analyze the pile layout only for the three remaining motions: X and Z deflections and Y rotation. If B_{55} is zero, a similar procedure will be followed using only the appropriate deflections. Pile cap instabilities other than those just described will prevent a solution by CPGA. However, instabilities of rows of pinned piles not aligned along the global X or Y axis can be eliminated by the user by specifying the pile stiffness coefficients directly (data input item e, paragraph 24) and providing a small nonzero value for the appropriate stiffness to prevent instability.

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APPENDIX A: INPUT DATA SUMMARY

1. Listed below are the data input items. Refer to pages 13 through 28 for a more detailed description.

a. Title

b. "PROP" E I1 I2 A C33 B66 list

E = modulus of elasticity of pile material (K/IN^2)

I1 = moment of inertia about 1 axis (IN^4)

I2 = moment of inertia about 2 axis (IN^4)

A = cross-sectional area of pile (IN^2)

C33 = axial stiffness modifier for embedded portion of pile

B66 = torsional stiffness (IN-KIP)/RAD

list = list of piles to which properties apply

c. "SOIL" PSOIL ESOIL LENGTH L LU list

PSOIL = "ES or NH"

ESOIL = value of ES or NH (K/IN^2 or K/IN^3)

LENGTH = "LEN or TIP"

L = pile length or Z coordinate of tip (FT)

LU = unsupported height of pile above groundline (FT)

list = list of piles to which soil properties apply

d. "PIN OR FIX" list

"PIN or FIX" = fixity

list = list of piles to which fixity applies

e. "BIJ" B11 B22 B33 B44 B55 B66 B15 B24 list

B11, B22 = lateral along 1 axis and 2 axis

B33 = axial stiffness

B44, B55 = rotational stiffness about 1 axis and 2 axis

B66 = torsional stiffness

B15, B24 = coupling stiffness, moment required to cause unit lateral displacement, or force required to cause unit rotation

list = list of piles to which the specified stiffness coefficients apply

f. "TENSION" CT list

CT = tension pile axial stiffness modifier

list = list of piles to which torsion modifier applies

g. "ALLOW" SHAPE AC AT ACC ATT AM1 AM2 list

SHAPE = R (round piles) or H (H piles)

AC = allowable axial compression load (KIPS)

AT = allowable axial tension load (KIPS)

ACC, ATT = allowable axial compressive and tensile forces for combined bending (KIPS)

AM1, AM2 = allowable moments for combined bending (IN-KIPS)

list = list of piles to which allowables apply

h. "DLS" SHAPE AC AT PO PT PB MB MO ST W list

SHAPE = R (round piles) or S (square piles)

AC = allowable compression load (KIPS)

AT = allowable tension load (KIPS)

PO = axial design load strength of piles in compression (KIPS)

PT = axial design load strength of piles in tension (KIPS)

PB = axial design load strength at balance conditions (KIPS)

MB = design moment strength at balanced conditions (IN-KIPS)

MO = design moment strength under pure flexure (IN-KIPS)

ST = structure type; "H" = hydraulic; "N" = nonhydraulic structures

W = diameter of round pile or width of square pile (IN)

list = list of piles to which the design load strengths apply

i. "ASC" SHAPE A S FPC IPC FA FT list

SHAPE = S (square) or R (round or octagonal)

A = cross-sectional area (IN^2)

S = section modulus (IN^3)

FPC = concrete stress due to final prestress force (KSI)

IPC = concrete stress due to initial prestress force (KSI)

FA = allowable compressive stress in concrete (KSI)

FT = allowable tensile stress in concrete (KSI)

list = list of piles to which allowable stress data apply

j. "UNSUP" MATL CM1 CM2 PCR1 PCR2 ST list

MAT1: "S" = steel, "T" = timber, "C" = concrete

CM1, CM2 = moment diagram shape factor for the 1 and 2 axes, respectively

PCR1, PCR2 = critical load for buckling about the 1 and 2 axes, respectively (KIPS)

ST = structure type; "H" = hydraulic structure; "N" = nonhydraulic structure

list = list of piles to which unsupported pile data applies

k. "PMAXMOM" KMP1 KMP2 list

KMP1 = moment factor for M1 (IN)

KMP2 = moment factor for M2 (IN)

list = list of piles to which factors apply

l. "FUNSMOM" KMF1U KMF2U list

KMF1U = moment factor for M1U (IN)

KMF2U = moment factor for M2U (IN)

list = list of piles to which factors apply

m. "FOVSTR" OSF OSFT list (defaults = 1.0)

OSF = overstress factor allowed

OSFT = overstress factor allowed for pile tension load

list = list of load cases to which overstress factors apply

n. "BATTER" BAT list (default = 100)

BAT = slope ratio of batter

list = list of piles to which batter applies

o. "ANGLE" ANG list (default = 0.0)

ANG = pile orientation angle (DEGREES)

list = list of piles to which angle applies

p. "PILE" PN1 X1 Y1 Z1 PN1 X2 Y2 Z2 . . . . (pile coordinates)

PN_n = pile number

X_n, Y_n, Z_n, = X, Y, Z coordinates of pile (FT)

q. "ROW" AXIS NP PN1 SP1 SP2 . . . (pile row generation)

AXIS = axis to which the row is parallel "X" or "Y"

NP = number of piles in row, including PN1

PN1 = pile number of first pile in row

SP_n = list of pile spacings (NP-1) (FT)

r. "REPEAT" NR SP1 SP2 . . . . (repeat rows of piles)

NR = number of rows of piles, including the original row

SP_n = list of row spacings (NR-1)(FT)

s. "ARC" CENTER RAD ANG PN1 NP SP1 SP2 . . . (pile arc generation)

CENTER = X , Y , Z coordinates of center of curvature (FT)

RAD = radius of arc (FT)

ANG = angle to first pile on arc (DEG)

PN1 = pile number for first pile

NP = number of piles in arc, including PN1

SP_n = list of pile spacings (DEG)

t. "REPEAT" NA SP1 SP2 . . . (Repeat arcs of piles)

NA = number of arcs of piles, including the original

SP_n = list of arc radial spacings (NA-1)(FT)

u. "DUP" PN COORD AXIS list (duplicate pile zones)

PN = pile number for first duplicate pile

COORD = new X , Y , Z coordinates for first pile in list (FT)

AXIS = axis specification for mirror images "X" or "Y" or "N"

list = list of pile numbers to be duplicated

v. "ROT" X Y ANG list (rotate pile zones)

X, Y = X and Y coordinates of center of rotation (FT)

ANG = angle of rotation (DEG)

list = list of piles in zone to be rotated

w. "SLOPE" PLANE SLP AXY AZ list (slope of set of pile rows)

PLANE = plane in which the slope exists "XZ" or "YZ"

SLP = slope of pile cap (SLP = H/V)

AXY = X or Y coordinate of Point "A" (FT)

AZ = Z coordinate of Point "A" (FT)

list = list of piles to which the slope applies

x. "DELETE" RENUM IPRI list

RENUM = "REN" or "NREN"

IPRI = "Y" to print resequencing

= "N" not to print

list = list of piles to be deleted

y. "LOAD" LCN PX PY PZ MX MY MZ

LCN = load case number

PX, PY, PZ = applied forces along the X , Y , and Z axes (KIPS)

MX, MY, MZ = applied moments at the origin of the global coordinate system about X , Y , and Z axis (FT-KIPS)

z. "DISP" TYPE D list (specified displacements)

TYPE = "DX", "DY", "DZ", "RX", "RY", or "RZ"

D = displacement magnitude (IN or DEG)

list = list of load cases to which displacements apply

aa. "TOUT" list (default = 1 , 3 , 4 , 6)

list = 1 Pile and soil properties

= 2 Pile locations and batters

= 3 Pile group stiffness matrix

= 4 Pile cap displacements

= 5 Local forces acting on selected piles

= 6 Forces acting on overstressed piles

= 7 Pile forces in global coordinates

bb. "FOUT" list OFN (default = 1 , 3 , 4 , 6)

OFN = output file name

cc. "PSO" list (default = Pile #1)

list = piles for stiffness matrix output

dd. "PCDO" X1 Y1 Z1 X2 Y2 Z2, ... (default = none)

XN YN ZN = coordinates of point on pile cap where displacements will be calculated (FT)

ee. "PFO" list (default = none)

list = piles for pile force output

ff. "PLB" list

list = piles for which pile geometry will be output

gg. "FPL" PFN

PFN = plot file name for CPGG

hh. "DAT"

APPENDIX B: EXAMPLE PROBLEMS

Example Problem 1, Hrennikoff Example - Medium Soil

1. This problem was taken from Hrennikoff's (1950) paper entitled "Analysis of Pile Foundation with Batter Piles." Figures B1 through B5 illustrate this example, first showing the retaining wall as a two-dimensional (2-D) problem with the local and global geometry and pile cap displacements.

Two-Dimensional Retaining Wall

2. The 2-D problem represents a retaining wall and is illustrated in Figure B1. The piles are timber, 9 in. in diameter, and 30 ft long. They are assumed to act as skin friction piles and the pile heads are assumed fixed. The soil is of medium strength with a constant ES of 312 psi. Allowable pile capacities are 50 kips in compression and 25 kips in tension.

3. Computations necessary for determining input items to the CPGA program are shown in Figure B2 and the accompanying calculations. Input for the program is run in the interactive mode with the output following. Figures B3, B4, and B5 show pile forces in local and global geometry and pile cap displacements. Comparisons of the results from CPGA and results from the Hrennikoff paper are shown in these figures and calculations.

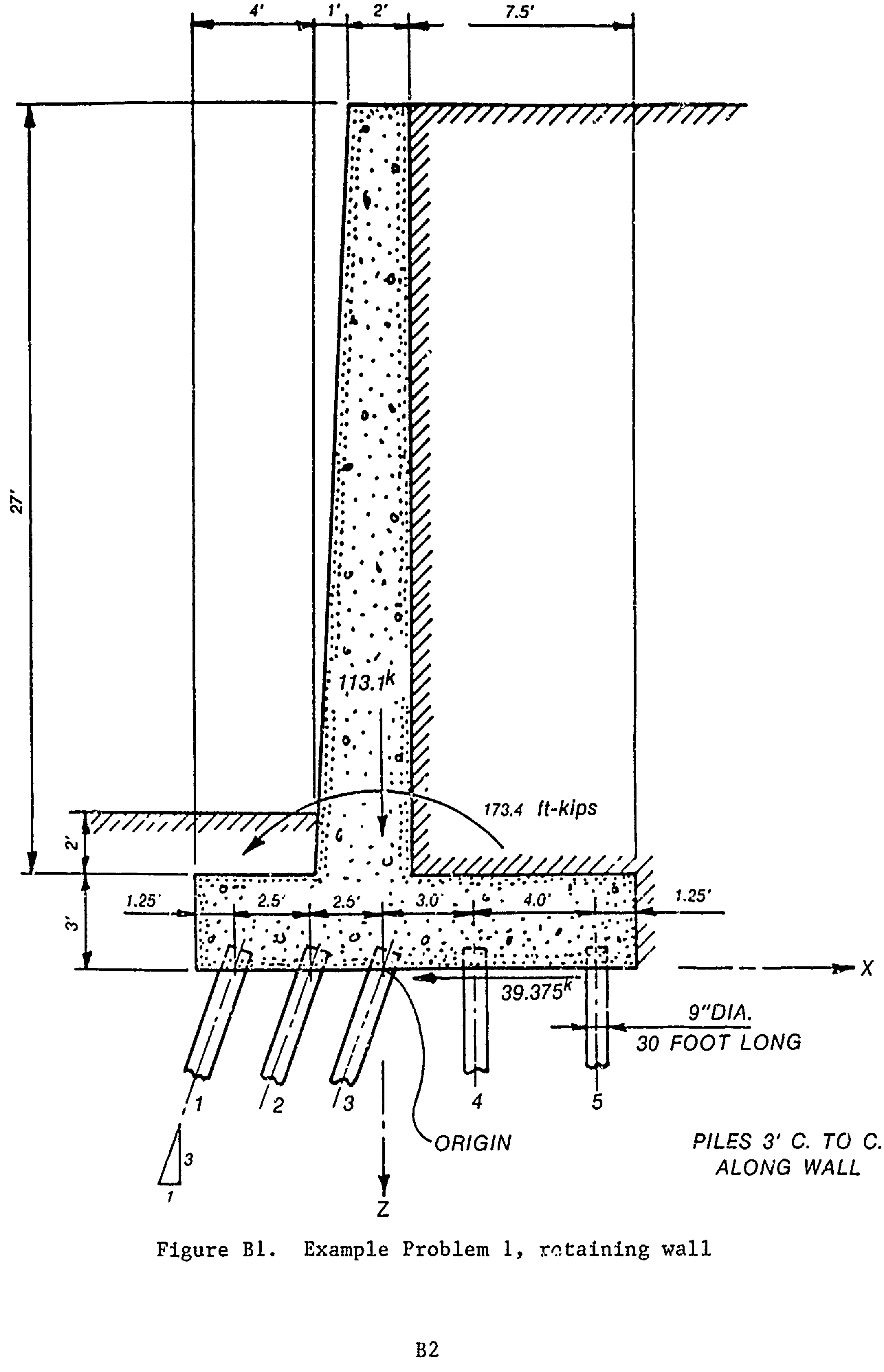
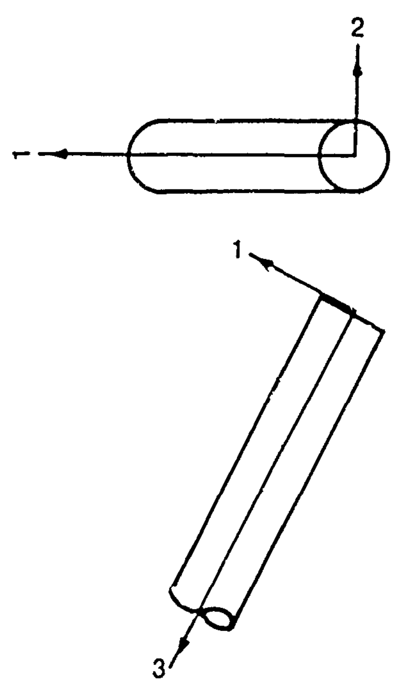


Figure B1. Example Problem 1, retaining wall

PILE ORIENTATION
LOCAL COORDINATE SYSTEM



9" ROUND PILES

$$I = \frac{\pi d^4}{64} = \frac{\pi (9)^4}{64} = 322.06 \text{ in}^4$$

$$A = \frac{\pi (9)^2}{4} = 63.6 \text{ in}^2$$

PROPERTIES	
E = 1500 ksi	FIXITY - FIXED
I1 = 322.06 in.^{4}	C33 = 2.0
I2 = 322.06 in.^{4}	B66 = 0.0
A = 63.6 in.^{2}	
L = 30.0 ft	
ES = 0.312 ksi	

Figure B2. Two-dimensional problem

Allowables:

$AC = 50.0^k$

$AT = 25.0^k$

Southern Pine F_{ac} = 1,000 psi

$ACC = (F_{ac})(A) = (1.000)(63.6) = 63.6^k$

$ATT = (F_{at})(A) = (2.000)(63.6) = 127.2^k$

Southern Pine F_{at} = 2,000 psi

$AM1 = F_b S1 \qquad S1 = \dfrac{I1}{C} = \dfrac{322.06}{4.5} = 71.6 \text{ in.}^3$

$AM1 = (2.000)(71.6) = 143.2$ in.-kips

Southern Pine F_b = 2,000 psi

$AM2 = F_b S2 \qquad S2 = \dfrac{I2}{C} = \dfrac{322.06}{4.5} = 71.6 \text{ in.}^3$

$AM2 = (2.000)(71.6) = 143.2$ in.-kips

Applied loads:

Load Case Number	PX (kips)	PY (kips)	PZ (kips)	MX (ft-kips)	MY (ft-kips)	MZ (ft-kips)
1	79.375	0	113.1	0	173.4	0

EXAMPLE PROBLEM NO. 1

INPUT TO CPGA

Data Group

(a) TITLE

EXAMPLE PROBLEM 1

(b) PILE PROPERTIES

	E	I1	I2	A	C33	B66	LIST
PROP	1500	322.06	322.06	63.6	2.0	0	ALL

(c) SOIL DESCRIPTION

	PSOIL	ESOIL	LENGTH	L	LU	LIST
SOIL	ES	0.312	L	30.0	0	ALL

(d) FIXITY

FIXITY	LIST
FIX	ALL

(e) PILE STIFFNESS - Omit (Based on Soil and Pile Properties)

(f) TENSION PILE STIFFNESS MODIFIER - Omit (Not Desired)

(g) ALLOWABLE LOADS STEEL AND TIMBER PILES

	SHAPE	AC	AT	ACC	ATT	AM1	AM2	LIST
ALLOW	R	50	25	63.6	127.2	143.2	143.2	ALL

(h) DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE OR REINFORCED CONCRETE PILES - Omit (Not Applicable)

(i) ALLOWABLE STRESS CHECK - PRESTRESSED CONCRETE PILES - Omit (Not Applicable)

(j) UNSUPPORTED PILE DATA - Omit (Not Applicable)

(k) DESIGN MOMENT FACTORS FOR PINNED PILE - Omit (Not Applicable)

(l) MOMENT FACTORS FOR FIXED UNSUPPORTED PILES - Omit (Not Applicable)

(m) OVERSTRESSED FACTORS - Omit (Default to 1.0)

(n) PILE BATTER

	BAT	LIST	
BATTER	3.0	1 2 3	(Vertical Piles 4 & 5 Default to 0)

(o) ANGLE TO BATTER DIRECTION

	ANG	LIST
ANGLE	180	ALL

(p) PILE COORDINATES

	PN1	X1	Y1	Z1
PILE	1	-5.0	0	0

(q) PILE ROW GENERATION

	AXIS	NP	PN1	SP1	SP2	SP3	SP4
ROW	X	5	1	2.5	2.5	3.0	4.0

(r) REPEAT ROWS OF PILES - Omit (Not Applicable)

(s) PILE ARC GENERATION - Omit (Not Applicable)

(t) REPEAT ARCS OF PILES - Omit (Not Applicable)

(u) DUPLICATE PILE ZONES - Omit (Not Applicable)

(v) ROTATE PILE ZONES - Omit (Not Applicable)

(w) SLOPED BASE DESCRIPTION - Omit (Not Applicable)

(x) PILE DELETION - Omit (Not Applicable)

(y) LOAD CASES

	LCN	PX	PY	PZ	MX	MY	MZ
LOAD	1	-39.375	0	113.1	0	173.4	0

(z) SPECIFIED PILE CAP DISPLACEMENTS - Omit (Not Desired)

(aa) OUTPUT AT TERMINAL

	LIST					
TOUT	1	2	3	4	5	7

(bb) OUTPUT TO FILE - Omit (Not Desired)

(cc) PILE STIFFNESS OUTPUT

	LIST
PSO	(Default to Pile #1)

(dd) PILE CAP DISPLACEMENT OUTPUT - Omit (Default to Origin)

(ee) PILE FORCE OUTPUT

	LIST
PFO	ALL

(ff) PILE COORDINATES OUTPUT - Omit (Default to print all coordinates)

(gg) PLOT FILE OPTION - Omit (Graphics not displayed)

```
*******************************
*  CORPS PROGRAM *  X0080     *
*    CDC VERSION * 86/09/02-A *
*******************************

CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE  88/04/07   RUN TIME  14.33.34


     FOR PILES WITH UNSUPPORTED HEIGHT:
          A. CPGA CANNOT CALCULATE PMAXMOM FOR NH TYPE SOIL
          B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
             NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
             WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

     ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


 DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
 ENTER F OR I.
? I
 ENTER NEW DATA FILE NAME
? X80D1



 INTERACTIVE INPUT OF YOUR DATA FILE.
 INPUT A ? IF MORE INFORMATION IS NEEDED ABOUT
 DATA BEING REQUESTED.


 ENTER TITLE OR * WHEN DONE. (71 CHARACTERS)
? EXAMPLE PROBLEM 1
 ENTER TITLE OR * WHEN DONE. (71 CHARACTERS)
? *
 ENTER PILE PROPERTIES OR * WHEN DONE.
 (E I1 I2 A C33 B66 LIST)
? 1500 322.06 322.06 63.6 2.0 0 ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER PILE PROPERTIES OR * WHEN DONE.
 (E I1 I2 A C33 B66 LIST)
? *
 ENTER SOIL DESCRIPTION OR * WHEN DONE.
 (PSOIL ESOIL LENGTH L LU LIST)
? ES 0.312 L 30.0 0 ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER SOIL DESCRIPTION OR * WHEN DONE.
 (PSOIL ESOIL LENGTH L LU LIST)
? *
```

```
 ENTER PINNED PILE-STRUCTURE CONNECTION OR * WHEN DONE.
 (LIST)
? *
 ENTER FIXED PILE-STRUCTURE CONNECTION OR * WHEN DONE.
 (LIST)
? ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER FIXED PILE-STRUCTURE CONNECTION OR * WHEN DONE.
 (LIST)
? *
 ENTER PILE STIFFNESS OR * WHEN DONE.
 (B11 B22 B33 B44 B55 B66 B15 B24 LIST)
? *
 ENTER TENSION PILE STIFFNESS MODIFIER OR * WHEN DONE.
 (CT LIST)
? *
 ENTER ALLOWABLE LOADS OR * WHEN DONE.
 (SHAPE AC AT ACC ATT AM1 AM2 LIST)
? R 50.0 25.0 63.6 127.2 143.2 143.2 ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER ALLOWABLE LOADS OR * WHEN DONE.
 (SHAPE AC AT ACC ATT AM1 AM2 LIST)
? *

 ENTER DESIGN LOAD STRENGTHS OR * WHEN DONE.
 (SHAPE AC AT PO PT PB MB MO ST W LIST)
? *

 ENTER ALLOWABLE STRESS OR * WHEN DONE
 (SHAPE A S FPC IPC FA FT LIST)
? *
 ENTER UNSUPPORTED PILE DATA OR * WHEN DONE.
 (MATL CM1 CM2 PCR1 PCR2 ST LIST)
? *
 ENTER DESIGN MOMENT FACTORS FOR PINNED PILES OR * WHEN DONE.
 (KMP1 KMP2 LIST)
? *
 ENTER MOMENT FACTORS FOR FIXED UNSUPPORTED PILES OR * WHEN DONE.
 (KMF1U KMF2U LIST)
? *
```

```
 ENTER OVERSTRESS FACTORS OR * WHEN DONE.
 (OSF OSFT LIST)
? *
 ENTER PILE BATTER OR * WHEN DONE.
 (BAT LIST)
? 3.0 1 2 3
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER PILE BATTER OR * WHEN DONE.
 (BAT LIST)
? *
 ENTER ANGLE TO BATTER DIRECTION OR * WHEN DONE.
 (ANG LIST)
? 180 ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER ANGLE TO BATTER DIRECTION OR * WHEN DONE.
 (ANG LIST)
? *
 ENTER PILE COORDINATES OR * WHEN DONE.
 (PN1 X1 Y1 Z1 PN2 X2 Y2 Z2 . . .)
? 1 -5 0 0
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER PILE COORDINATES OR * WHEN DONE.
 (PN1 X1 Y1 Z1 PN2 X2 Y2 Z2 . . .)
? *
 ENTER PILE ROW GENERATION OR * WHEN DONE.
 (AXIS NP PN1 SP1 SP2 . . .)
? X 5 1 2.5 2.5 3.0 4.0
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER PILE ROW GENERATION OR * WHEN DONE.
 (AXIS NP PN1 SP1 SP2 . . .)
? *
 ENTER PILE ROW REPETITION OR * WHEN DONE.
 (NR SP1 SP2 . . .)
? *
 ARE YOU DONE WITH ROWS? (Y OR N)
? Y
 ENTER PILE ARC GENERATION OR * WHEN DONE.
 (CENTER RAD ANG PN1 NP SP1 SP2 . . .)
? *
```

```
ENTER PILE ZONE DUPLICATION OR * WHEN DONE.
(PN COORD AXIS LIST)
? *
ENTER PILE ZONE ROTATION OR * WHEN DONE.
(X Y ANG LIST)
? *
ENTER SLOPED BASE OR * WHEN DONE.
(PLANE SLP AXY AZ LIST)
? *
ENTER PILE DELETION OR * WHEN DONE.
(RENUM IPRI LIST)
? *
ENTER LOAD CASES OR * WHEN DONE.
(LCN PX PY PZ MX MY MZ)
? 1 -39.375 0 113.1 0 173.4 0
CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
ENTER LOAD CASES OR * WHEN DONE.
(LCN PX PY PZ MX MY MZ)
? *
ENTER SPECIFIED DISPLACEMENTS OR * WHEN DONE.
(TYPE D LIST)
? *
ENTER OUTPUT AT TERMINAL OR * WHEN DONE.
(LIST)
? 1 2 3 4 5 7
ENTER OUTPUT TO FILE OR * WHEN DONE.
(LIST FNAME)
? *
ENTER PILE LOCATION AND BATTER OR * WHEN DONE
(LIST)
? *
ENTER PILE STIFFNESS OUTPUT OR * WHEN DONE.
(LIST)
? 1
CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
ENTER PILE STIFFNESS OUTPUT OR * WHEN DONE.
(LIST)
? *
ENTER PILE CAP DISPLACEMENT OUTPUT OR * WHEN DONE.
(X1,Y1,Z1,X2,Y2,Z2 ...)
? *
```

```
 ENTER PILE FORCE OUTPUT OR * WHEN DONE.
 (LIST)
? ALL
 CONTINUATION OF ABOVE LIST OR * WHEN DONE.
? *
 ENTER PILE FORCE OUTPUT OR * WHEN DONE.
 (LIST)
? *

 IS THIS A DATA CHECK RUN? (Y OR N)
? N

 WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
? N
 SHOULD THE INPUT FILE NAMED 'X80D1  ' BE LISTED? (Y OR N)
? Y
 1000 EXAMPLE PROBLEM 1
 1010 PRO 1500 322.06 322.06 63.5 2.5 0 ALL
 1020 SOI ES 0.312 L 30.0 0 ALL
 1030 FIX ALL
 1040 ALL R 50.0 25.0 63.6 127.2 143.2 143.2 ALL
 1050 BAT 3.0 1 2 3
 1060 ANG 180 ALL
 1070 PIL 1 -5 0 0
 1080 ROW X 5 1 2.5 2.5 3.0 4.0
 1090 LOA 1 -39.375 0 113.1 0 173.4 0
 1100 TOU 1 2 3 4 5 7
 1110 PSO 1
 1120 PFO ALL
 1130 FPL N



 ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
 DO YOU WISH TO HAVE AN ANALYSIS OF YOUR INPUT FILE? (Y OR N)
? Y
 EXAMPLE PROBLEM 1


 THERE ARE   5 PILES AND
             1 LOAD CASES IN THIS RUN.

 ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                                            X          Y          Z
                                          -----      -----      -----
 WITH DIAGONAL COORDINATES = (     -5.00 ,       .00 ,       .00 )
                             (      7.00 ,       .00 ,       .00 )
```

****

PILE PROPERTIES AS INPUT

E	I1	I2	A	C33	B66
KSI	IN**4	IN**4	IN**2		
.15000E+04	.32206E+03	.32206E+03	.63600E+02	.20000E+01	.00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

ALL

****

SOIL DESCRIPTIONS AS INPUT

ES	ESOIL	LENGTH	L	LU
	K/IN**2		FT	FT
	.31200E+00	L	.30000E+02	.00000E+00

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

ALL

****

PILE STIFFNESSES AS CALCULATED FROM PROPERTIES

.15565E+02	.00000E+00	.00000E+00	.00000E+00	.38823E+03	.00000E+00
.00000E+00	.15565E+02	.00000E+00	-.38823E+03	.00000E+00	.00000E+00
.00000E+00	.00000E+00	.53000E+03	.00000E+00	.00000E+00	.00000E+00
.00000E+00	-.38823E+03	.00000E+00	.19368E+05	.00000E+00	.00000E+00
.38823E+03	.00000E+00	.00000E+00	.00000E+00	.19368E+05	.00000E+00
.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00

THIS MATRIX APPLIES TO THE FOLLOWING PILES -

1

****

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X FT	Y FT	Z FT	BATTER	ANGLE	LENGTH FT	FIXITY
1	-5.00	.00	.00	3.00	180.00	30.00	F
2	-2.50	.00	.00	3.00	180.00	30.00	F
3	.00	.00	.00	3.00	180.00	30.00	F
4	3.00	.00	.00	V	180.00	30.00	F
5	7.00	.00	.00	V	180.00	30.00	F

						150.00	

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	-39.4	.0	113.1	.0	173.4	.0

****

ORIGINAL PILE GROUP STIFFNESS MATRIX

.23215E+03	-.55402E-06	-.46299E+03	.00000E+00	-.12008E+05	.15298E-04
-.55402E-06	.77823E+02	.16620E-05	-.18814E+04	.49861E-04	.98629E+02
-.46299E+03	.16620E-05	.24957E+04	.13222E-05	-.20162E+05	-.49861E-04
.00000E+00	-.18014E+04	.13222E-05	.91027E+05	.60522E-04	.39908E+04
-.12008E+05	.49861E-04	-.20162E+05	.60522E-04	.66990E+07	-.25556E-02
.15298E-04	.98629E+02	-.49861E-04	.39908E+04	-.25556E-02	.22795E+06

5 PILES 1 LOAD CASES

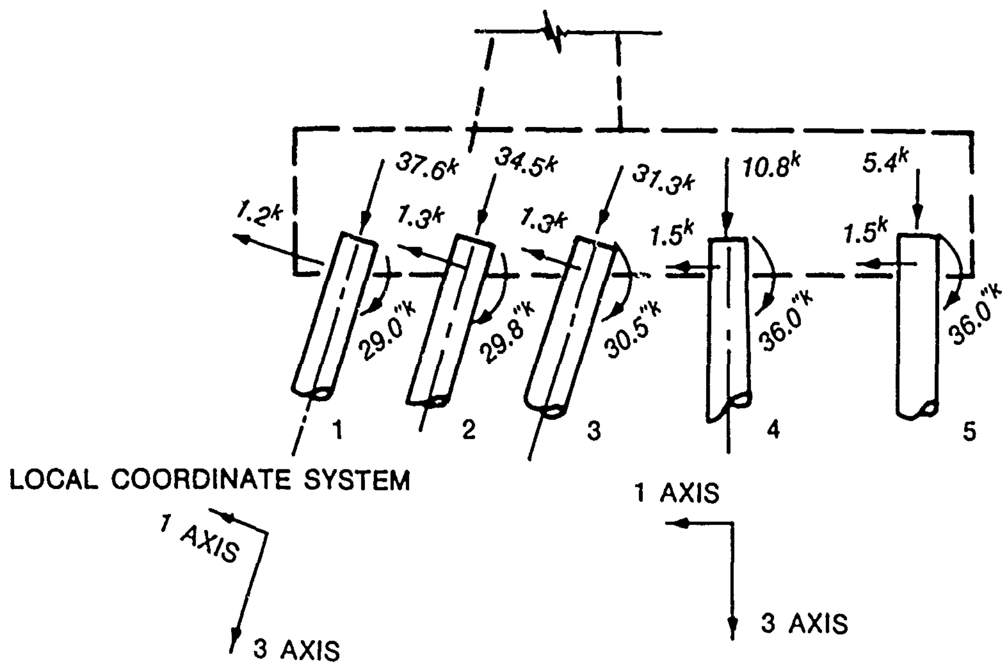
LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	-.1032E+00	-.3035E-08	.2787E-01	-.8406E-10	.2095E-03	.1780E-10

```
*****************************************************************************

        PILE FORCES IN LOCAL GEOMETRY

            M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
            * INDICATES PILE FAILURE
            # INDICATES CBF BASED ON MOMENTS DUE TO
                        (F3*EMIN) FOR CONCRETE PILES
            B INDICATES BUCKLING CONTROLS


LOAD CASE -    1

PILE    F1      F2      F3       M1       M2       M3   ALF  CBF
         K       K       K      IN-K     IN-K     IN-K

  1     1.2     .0     37.6       .0     29.0       .0  .75  .79
  2     1.3     .0     34.5       .0     29.8       .0  .69  .75
  3     1.3     .0     31.3       .0     30.5       .0  .63  .71
  4     1.5     .0     10.8       .0     36.0       .0  .22  .42
  5     1.5     .0      5.4       .0     36.0       .0  .11  .34

*****************************************************************************

        PILE FORCES IN GLOBAL GEOMETRY

LOAD CASE -    1

PILE        PX        PY        PZ         MX         MY         MZ
             K         K         K        IN-K       IN-K       IN-K

   1      -13.1        .0      35.3         .0      -29.0         .0
   2      -12.1        .0      32.3         .0      -29.8         .0
   3      -11.1        .0      29.3         .0      -30.5         .0
   4       -1.5        .0      10.8         .0      -36.0         .0
   5       -1.5        .0       5.4         .0      -36.0         .0
SHOULD THE INPUT FILE NAMED 'X80D1  ' BE LISTED? (Y OR N)
? N


 ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
 RUN CPGA AGAIN? (Y OR N)
? N


 THE FOLLOWING FILES WERE GENERATED DURING THIS RUN.

          INTERACTIVE DATA INPUT FILE IS   X80D1
EXIT.
/
```



NOTE: Forces and moments shown are on pile head. Resisting forces and moments of pile to structure are equal and opposite.

Figure B3. Pile forces in local geometry

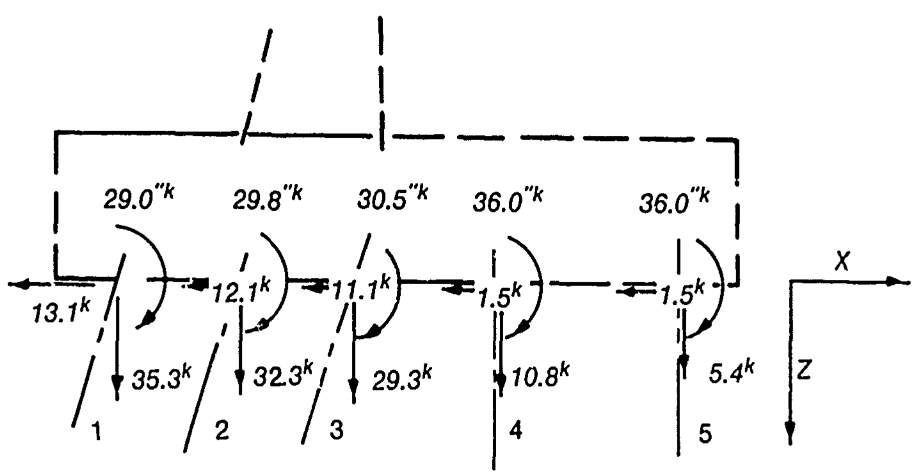


Figure B4. Pile forces in global geometry

4. Comparison of pile forces obtained by the CPGA program (output item - Pile Forces in Local Geometry) with the forces obtained by Hrennikoff (1950)(Case 6 in sample problem) shows close agreement.

Pile No.		Hrennikoff	CPGA
1	Axial force (KIPS)	37.6	37.6
	Trans force (KIPS)	1.25	1.2
	Moment at pile head (in.-k)	29.0	29.0
2	Axial force (KIPS)	34.5	34.5
	Trans force (KIPS)	1.28	1.3
	Moment at pile head (in.-k)	30.0	29.8
3	Axial force (KIPS)	31.3	31.3
	Trans force (KIPS)	1.31	1.3
	Moment at pile head (in.-k)	31.0	30.5
4	Axial force (KIPS)	10.8	10.8
	Trans force (KIPS)	1.53	1.5
	Moment at pile head (in.-k)	36.0	36.0
5	Axial force (KIPS)	5.5	5.4
	Trans force (KIPS)	1.53	1.5
	Moment at pile head (in.-k)	36.0	36.0

5. Comparison of the pile cap displacements obtained by CPGA (output item - pile cap displacements) with the displacements obtained by Hrennikoff (1950), likewise, shows close agreement.

Hrennikoff computes D'_x, D'_z and R'_y p 370

$$D_x = \frac{D'_x}{n} \qquad D_z = \frac{D'_z}{n} \qquad R_y = \frac{R'_y}{n}$$

For skin friction piles:

$$n = \frac{2AE}{L} = \frac{2(63.6)(1,500)}{(30)(12)}$$

$$n = 530 \text{ k/in.}$$

Hrennikoff displacements	CPGA displacements
$D_x = \frac{-54.8}{530} = -0.103$ in.	-0.1032 in.
$D_z = \frac{14.75}{530} = 0.028$ in.	0.02787 in.
$R_y = \frac{0.1108}{530} = 0.0002091$ rad	0.0002095 rad

6. A check of CPGA output for Pile 4, using Equations 1 and 3 from Part I, User's Manual, is illustrated.

Equation 1 from User's Manual, paragraph 24g:

$$ALF = \left(\frac{F3}{AC}\right)\left(\frac{1}{OSF}\right) = \left(\frac{10.8}{50}\right)\left(\frac{1}{1.0}\right) = 0.216$$

0.22 from CPGA output

Equation 3 from User's Manual, paragraph 24g:

$$CBF = \left[\frac{F3}{ACC} + MF1\left(\frac{|M1|}{AM1}\right) + MF2\left(\frac{|M2|}{AM2}\right)\right]\frac{1}{OSF}$$

$$= \left[\frac{10.8}{63.6} + 0 + 1.0\left(\frac{36.\text{[illegible]}}{143.2}\right)\right]\frac{1}{1.0} = 0.170 + 0.251$$

$$= 0.421$$

0.42 from CPGA output

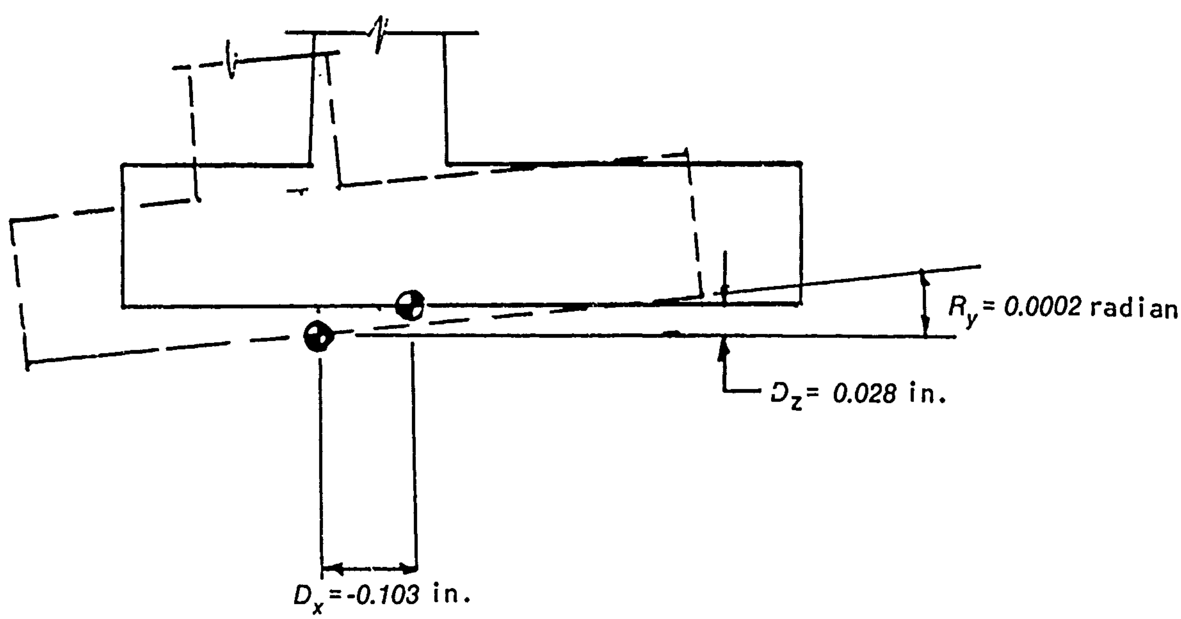


Figure B5. Pile cap displacements

Example Problems 2 and 2A, Floodwall with Prestressed Concrete Piles

7. This problem was taken from Lake Pontchartrain and Vicinity (Hurricane Protection), Barrier Plan, New Orleans Lakefront Levee, Monoliths 135 and 136.

Three-Dimensional Floodwall

8. This three-dimensional (3-D) problem represents an inverted "T"-type floodwall, illustrated in Figure B6, and consists of two "T"-wall monoliths oriented 90 deg to each other, with standard 12- by 12-in. prestressed concrete piles, 60 ft long. The piles are assumed to act as friction type, with pinned heads for bending and torsion. A constant ES of 200 psi, based on available geotechnical data for soft cohesive type soil, is used. Figures B7 and B8 are included to further show the construction and explain the different possible load cases. Allowable pile capacities are 80 kips in compression and 40 kips in tension.

9. The Bij matrix is developed by hand computations for program input. A tension axial stiffness modifier of 0.8 is illustrated along with the specified pile cap displacements.

10. Computations necessary for determining input items are shown along with input and output. Results of this problem are discussed and verified by hand computations.

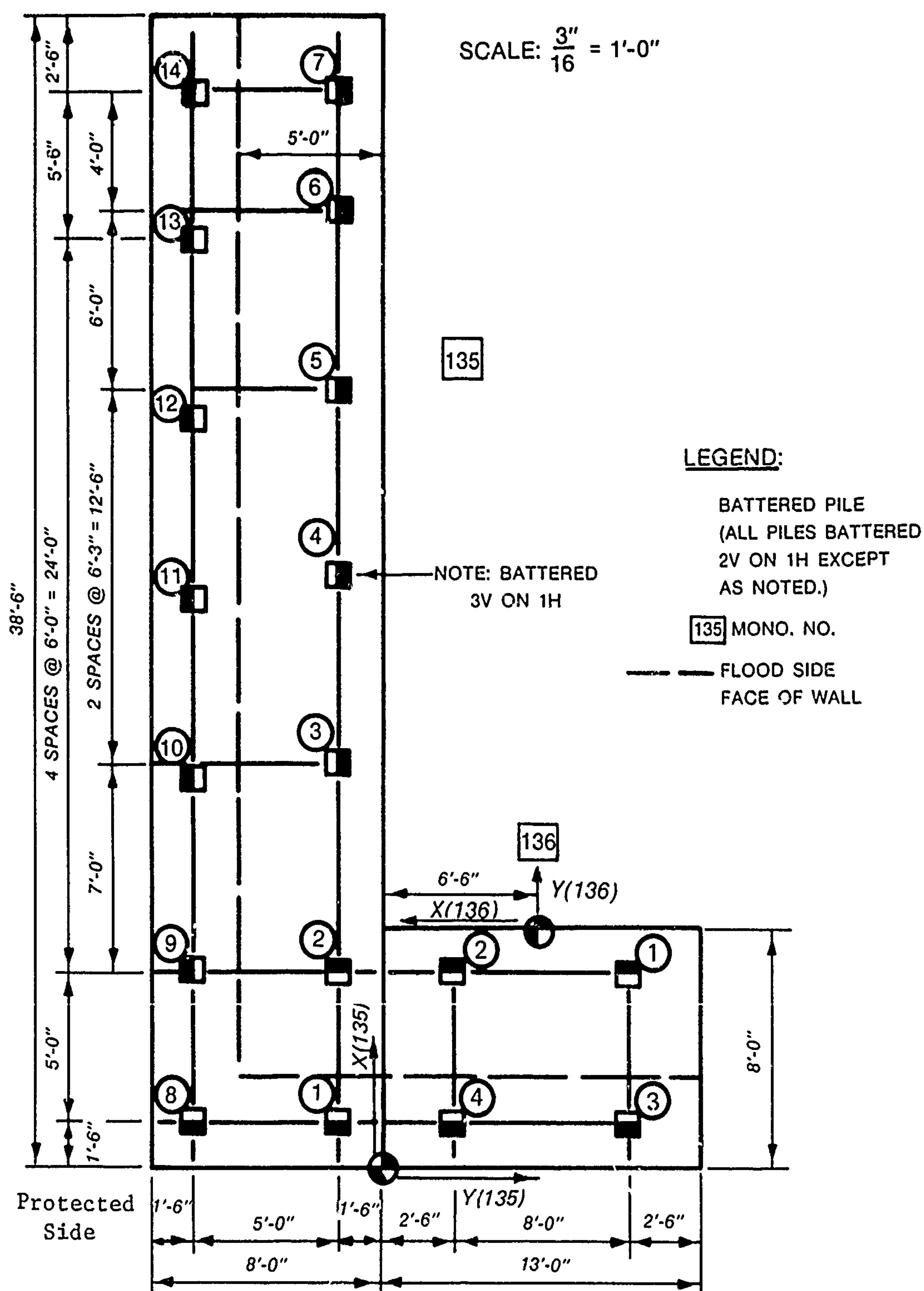


Figure B6. Monolith pile layout for Example Problem 2

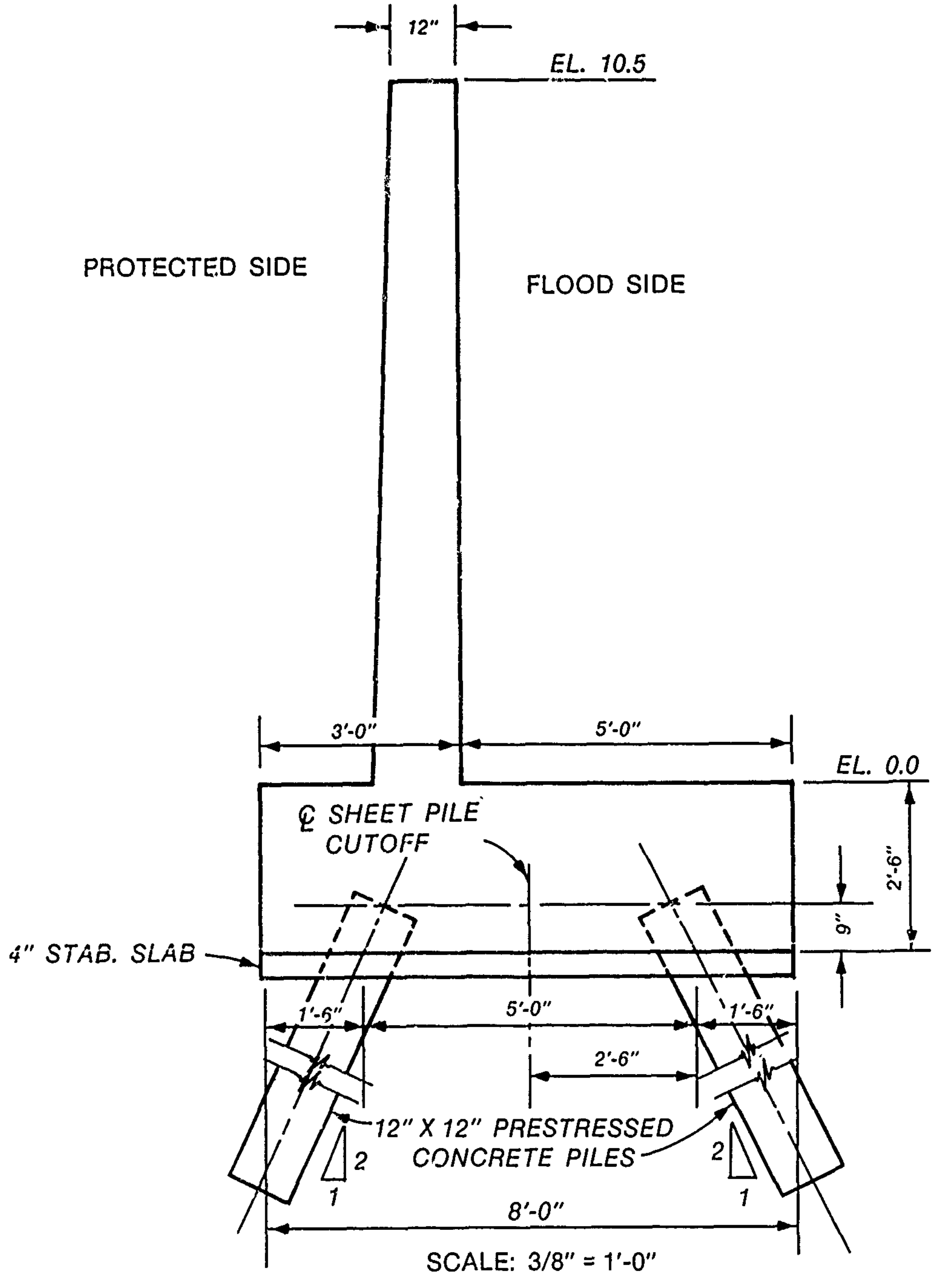


Figure B7. Typical wall section

LOAD CASE 1 - FLOOD WATER EL 10.5; IMPERVIOUS SOIL CONDITION

LOAD CASE 2 - FLOOD WATER EL 105; PERVIOUS SOIL CONDITION

LOAD CASE 3 - CONSTRUCTION (NORMAL CONDITION WITHOUT LOADS DUE TO SOIL, WATER OR UPLIFT)

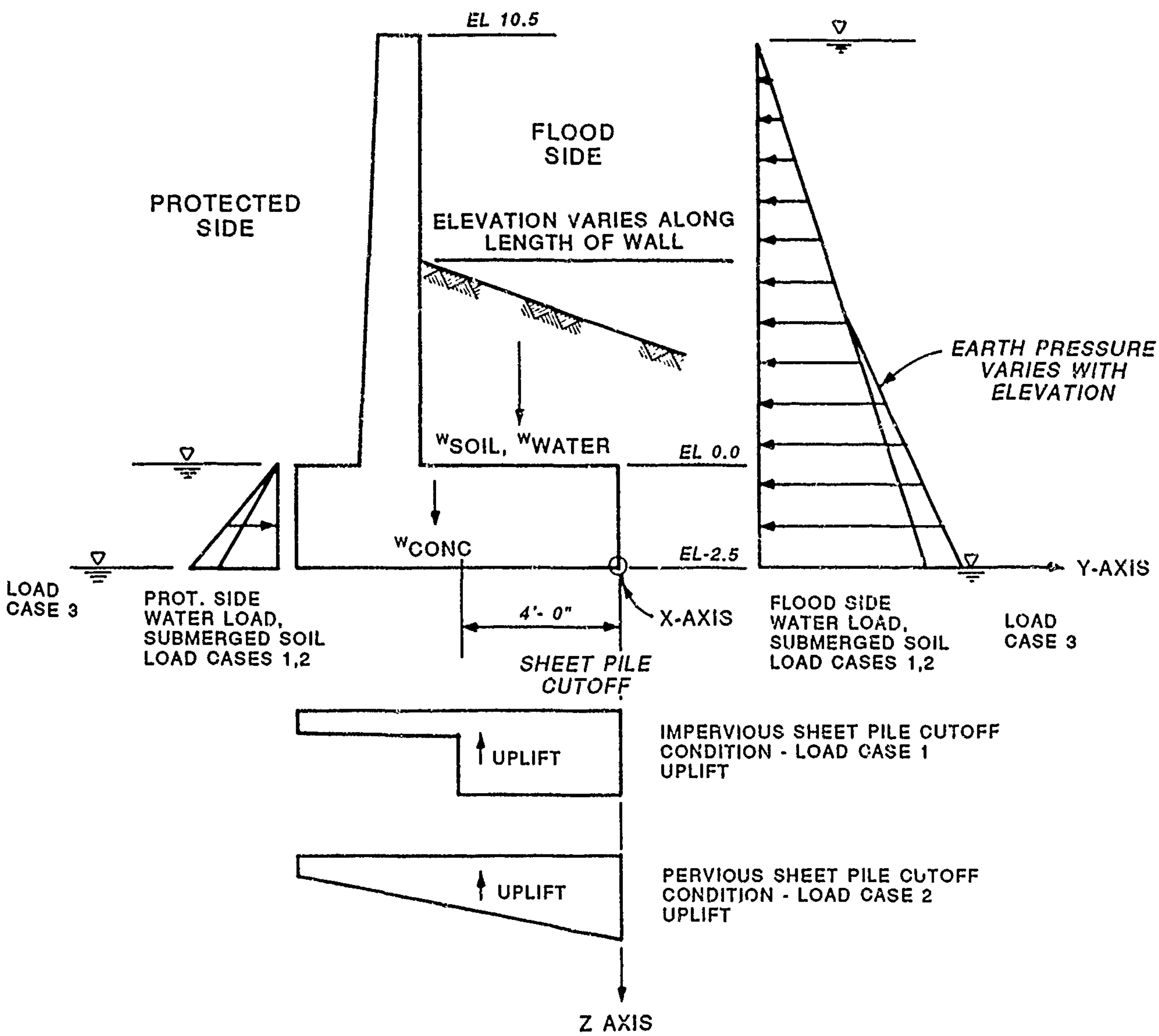


Figure B8. Three load cases

Three-dimensional floodwall, prestressed concrete piles, 12 in. × 12 in.:

$$E_{conc} = W^{1.5}\ 33\sqrt{f'_c} = 145^{1.5}\ 33\sqrt{5{,}000} = 4{,}074{,}281 \text{ psi}$$

$$= 4{,}074 \text{ ksi}$$

$$I_1 = \frac{12(12)^3}{12} = 1{,}728 \text{ in.}^4$$

$$I_2 = 1{,}728 \text{ in.}^4$$

$$S_1 = \frac{1{,}728}{6} = 288 \text{ in.}^3$$

$$S_2 = \frac{1{,}728}{6} = 288 \text{ in.}^3$$

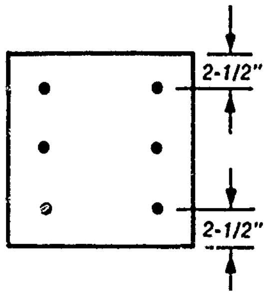
$$A = (12)(12) = 144 \text{ in.}^2$$

Properties	
$E = 4{,}074$ ksi	Fixity = pinned
$I_1 = 1{,}728$ in.^{4}	C33 = 2.0
$I_2 = 1{,}728$ in.^{4}	B66 = 0.0
$A = 144$ in.^{2}	
$L = 60.0$ ft	
ES = 0.200 ksi	

Allowables:

$$\left.\begin{array}{l} AC = 80 \text{ k} \\ \\ AT = 40 \text{ k} \end{array}\right\} \text{Based on soil allowables}$$

12 in. × 12 in. Prestressed concrete pile:



6--1/2" ϕ 250^k strands

$f'_c = 5$ ksi

Area per strand = 0.144 in.^{2}

$E_{strand} = 28{,}000$ ksi

Strands tensioned to 70% of ultimate

Assume 20% losses, therefore design load after losses is 80% of tensioning load:

$$\text{Design load} = 250(0.7)(0.8)(6)(0.144) = 120.96^k$$

$$\text{Final prestress FPC} = \frac{120.96}{(12)(12)} = 0.840 \text{ ksi}$$

$$\text{Tensioning load} = 250(0.7)(6)(0.144) = 151.2^k$$

$$\text{Initial prestress} = \frac{151.2}{(12)(12)} = 1.050 \text{ ksi}$$

Assume 5% immediate losses due to elastic shortening*

$$\text{IPC} = 0.95(1.050) = 0.9975 \text{ ksi}$$

---

* This assumption may be overly conservative in the computation of maximum compressive stresses. Studies show that a large percentage (70 to 80 percent) of the total losses (20 percent in this problem) occur within 6 months after the prestress is applied.

Allowable compressive concrete stress FA = $0.35f'_c = 1.750$ ksi

Compute PO:

$$PO = (0.85\ f'_c - 0.600\ FPC)A_c = (0.85(5) - 0.600(0.840))144$$

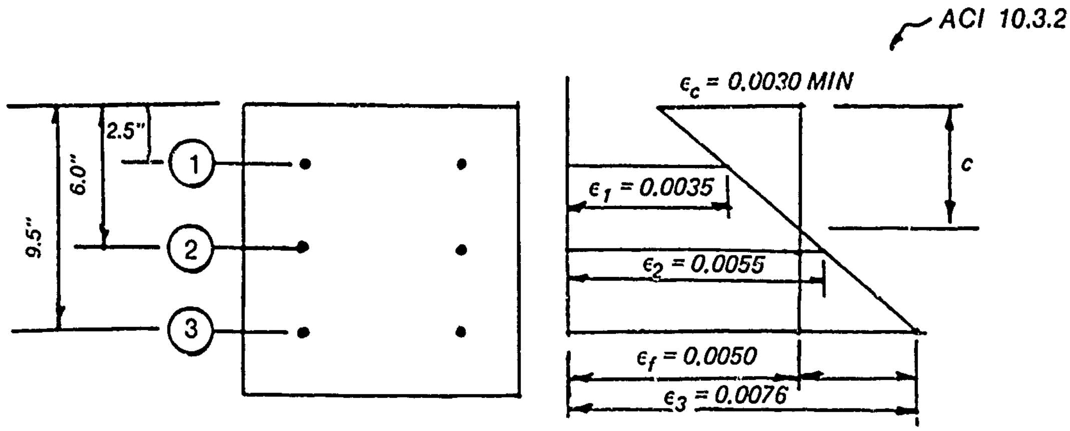
$$= 539.4^k$$

Compute PT:

Based on steel yielding

$$PT = F_y A_s = \overbrace{0.85(250)}^{F_y\ =\ 212.5\ \text{ksi}}(6)(0.144) = 183.6^k$$

Compute force and moment at balanced conditions (PB and MB input items)



Steel strain at final prestress:

$$\varepsilon_f = \frac{f_s}{E_s} = \frac{250(0.7)(0.8)}{28,000} = 0.0050$$

Steel strain at balanced condition:

$$\varepsilon_3 = \frac{F_y}{E_s} = \frac{212.5}{28,000} = 0.0076$$

$$\varepsilon_1 = \frac{2.5}{9.5}(0.0056) + 0.0020 = 0.0035$$

$$\varepsilon_2 = \frac{6.0}{9.5}(0.0056) + 0.0020 = 0.0055$$

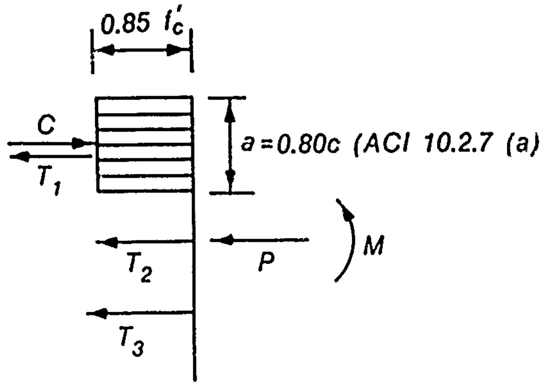
Force in strands:

$$T_3 = \varepsilon_3 E_s A_s$$
$$= 0.0076(28,000)(2)(0.144) = 61.3^k$$

$$T_2 = \varepsilon_2 E_s A_s$$
$$= 0.0055(28,000)(2)(0.144) = 44.4^k$$

$$T_1 = \varepsilon_1 E_s A_s$$
$$= 0.0035(28,000)(2)(0.144) = 28.2^k$$

Stress block



$$\frac{0.0056}{9.5} = \frac{0.0030}{c}$$

$$c = 5.09 \text{ in.}$$

$$a = 0.80\ c = 0.8(5.09) = 4.07 \text{ in.}$$

Pile width

$$C = a(12)(0.85f_c') = 4.07(12)(0.85)(5)$$

$$C = 207.6^k$$

$$PB = C - (T_1 + T_2 + T_3) = 207.6 - (28.2 + 44.4 + 61.3)$$

$$= 73.7^k$$

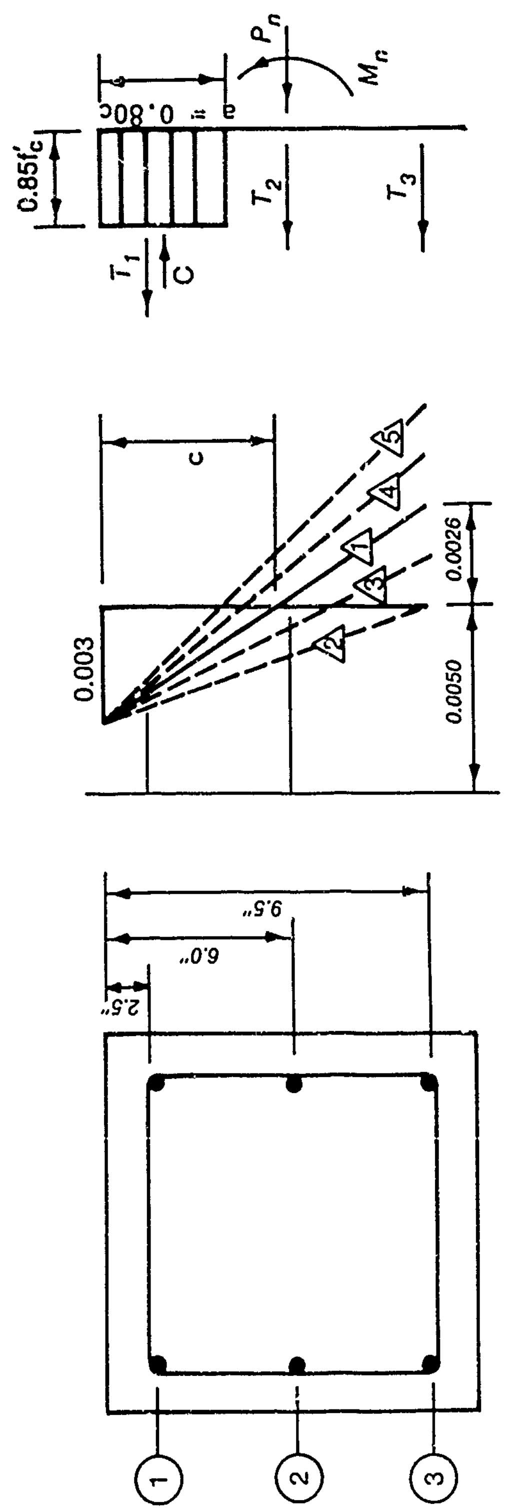
$$MB = C\left(6 - \frac{a}{2}\right) - T_1(3.5) + T_3(3.5)$$

$$= 207.6\left(6 - \frac{4.07}{2}\right) - 28.2(3.5) + 61.3(3.5)$$

$$= 823.1 - 98.7 + 214.6$$

$$= 939.0 \text{ in.-k}$$

CPGA Example Problem 2

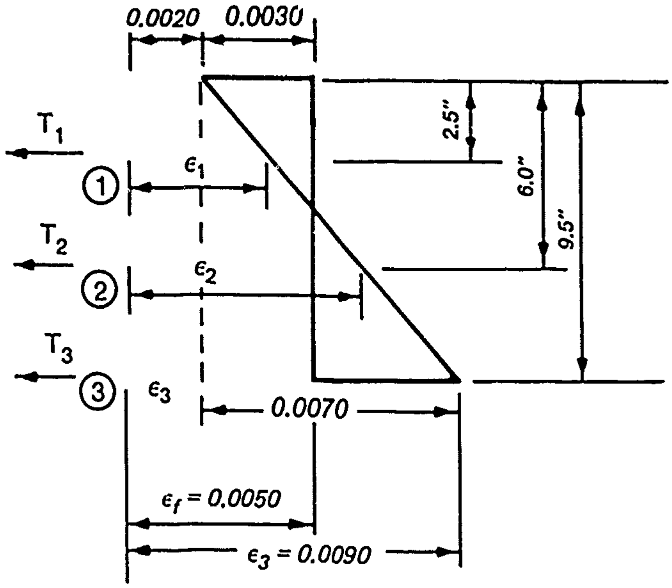


△	c (in.)	ϵ_1	ϵ_2	ϵ_3	T_1(k)	T_2(k)	T_3(k)	C	P_n(k)	M_n (in.-k)
1	5.09	0.0035	0.0055	0.0076	28.2	44.4	61.3	207.6	73.7 (P_B)	939.0 (M_B)
2	9.50	0.0028	0.0039	0.0050	22.6	31.4	40.3	387.6	293.3	914.7
3	6.63	0.0031	0.0047	0.0063	25.3	38.0	50.8	270.3	156.2	994.7
4	4.07	0.0038	0.0064	0.0090	30.6	51.6	61.3	166.1	22.6	833.3
5	3.65	0.0041	0.0069	0.0098	33.1	55.6	61.3	149.1	-0.9	775.6

BALANCE PT → 1

CALCULATION OF TYPICAL ORDINATES ON CURVE — POINT 4

LET $E_3 = 0.0090$



$$\varepsilon_1 = \frac{2.5}{9.5}(0.0070) + 0.0020 = 0.0018 + 0.0020 = 0.0038$$

$$\varepsilon_2 = \frac{6.0}{9.5}(0.0070) + 0.0020 = 0.0044 + 0.0020 = 0.0064$$

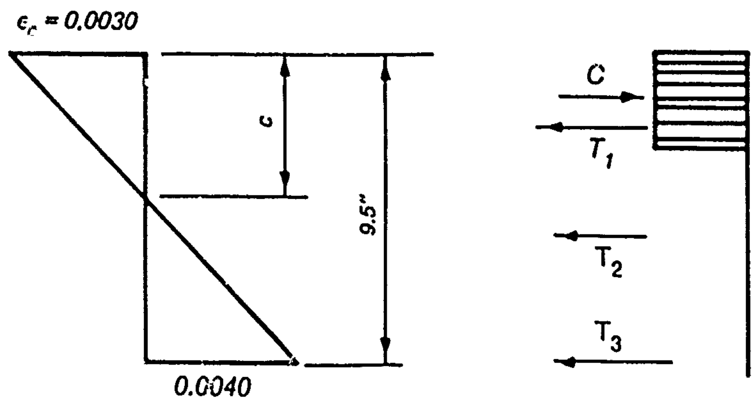
$$T_1 = \varepsilon_1 E_s A_s = (0.0038)(28{,}000)(2)(0.144) = 30.6^k$$

$$T_2 = \varepsilon_2 E_s A_s = (0.0064)(28{,}000)(2)(0.144) = 51.6^k$$

$$T_3 = \varepsilon_3 E_s A_s = (0.0090)(28{,}000)(2)(0.144) = 72.6^k \text{ - exceeds yield}$$

use $T_3 = 61.3^k$ (see p B26)

POINT 4



By similar triangles

$$\frac{c}{0.0030} = \frac{9.5}{0.0030 + 0.0040}$$

$$c = 4.07 \text{ in.}$$

$$a = 0.80c = 0.80(4.07) = 3.26 \text{ in.}$$

$$C = a(12)(0.85f'_c) = 3.26(12)(0.85)(5.0)$$

$$C = 166.1 \text{ kips}$$

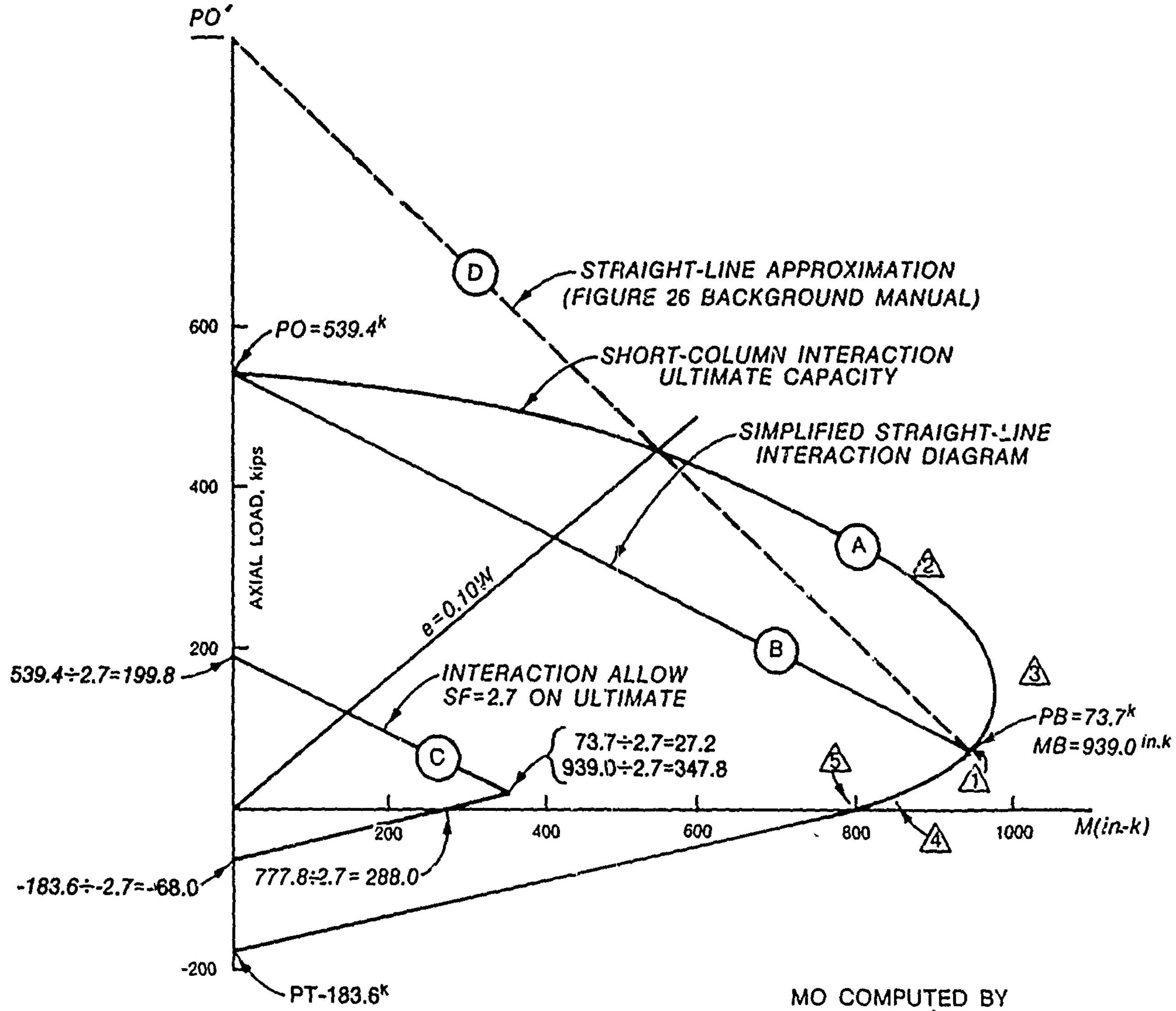
$$P_n = C - (T_1 + T_2 + T_3) = 166.1 - (30.6 + 51.6 + 61.3)$$

$$= 22.6^k$$

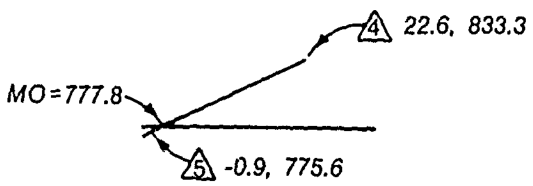
$$M_n = C\left(6 - \frac{a}{2}\right) - T_1(3.5) - T_2(0) + T_3(3.5)$$

$$= 166.1\left(6 - \frac{3.26}{2}\right) - 30.6(3.5) + 61.3(3.5) = 725.8 - 107.1 + 214.6$$

$$= 833.3 \text{ in-kips}$$

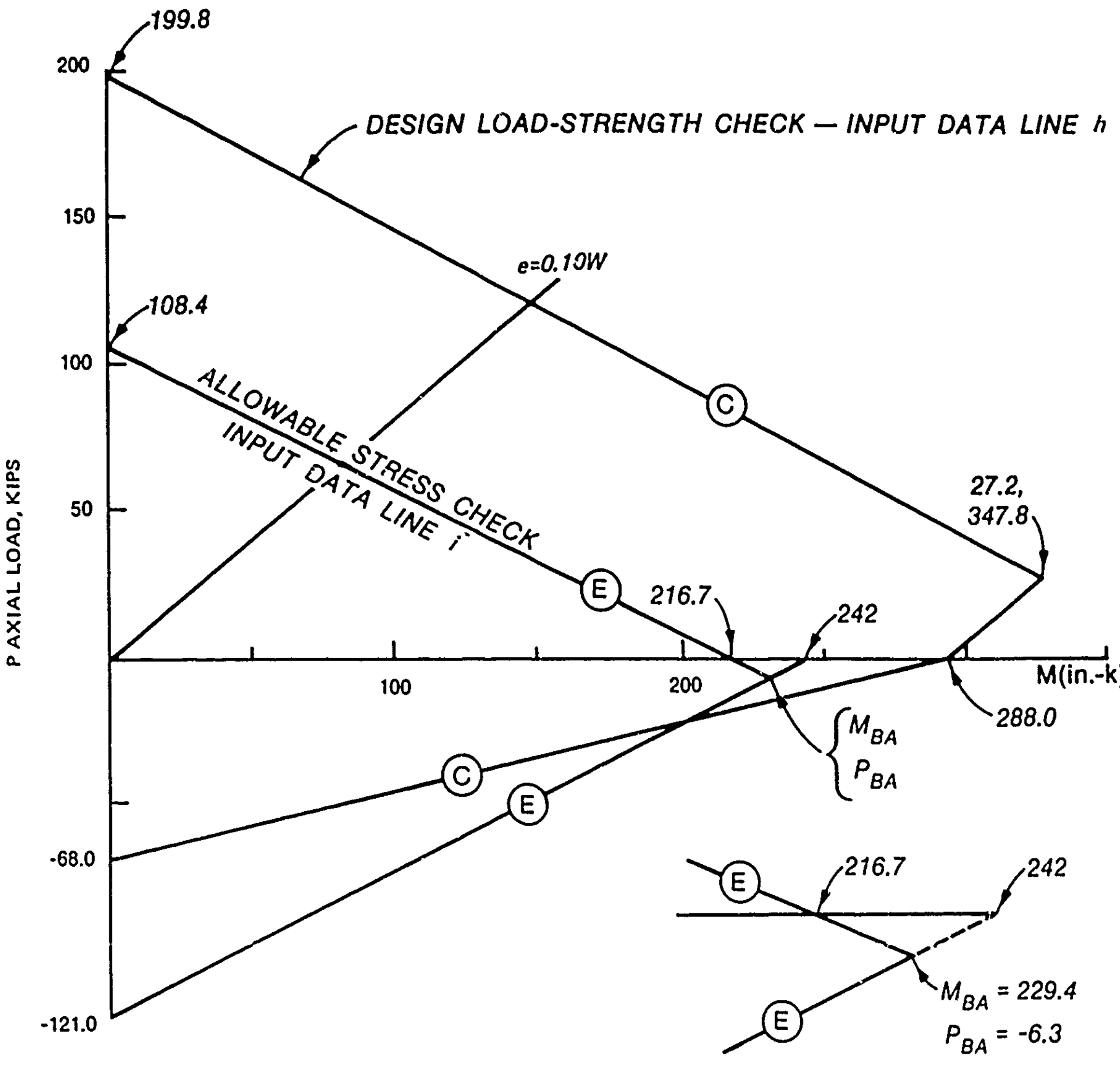


MO COMPUTED BY INTERPOLATION



$$MO = 775.6 + \frac{0.9}{22.6 - (-0.9)} (833.3 - 775.6) = 775.6 + 2.2$$
$$= 777.8^{in.k}$$

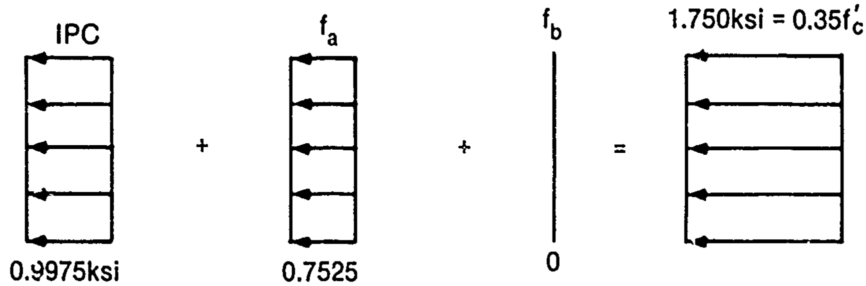
SHORT-COLUMN INTERACTION DIAGRAM FOR PILE


199.8
200
150
100
50
-68.0
-121.0
P AXIAL LOAD, KIPS
DESIGN LOAD-STRENGTH CHECK — INPUT DATA LINE h
e=0.10W
108.4
ALLOWABLE STRESS CHECK
INPUT DATA LINE i
C
E
27.2,
347.8
216.7
242
100
200
M(in.-k)
288.0
M_{BA}
P_{BA}
216.7
242
M_{BA} = 229.4
P_{BA} = -6.3

Allowable stress check (data line item i, paragraph 24, Part I)

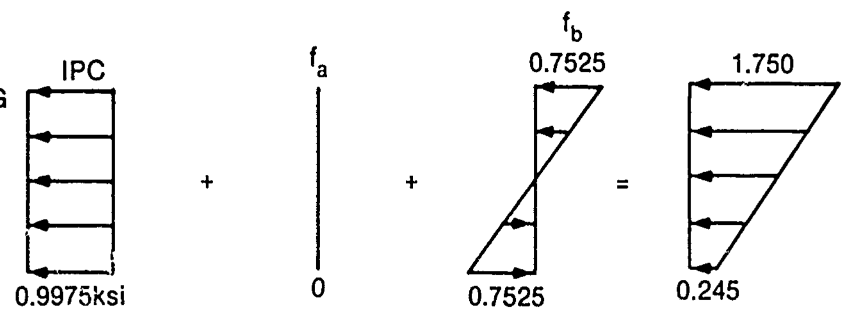
COMPRESSION PILES

MAX AXIAL



$P_{AC} = f_a\ A = (0.7525)(144) = 108.4^k$

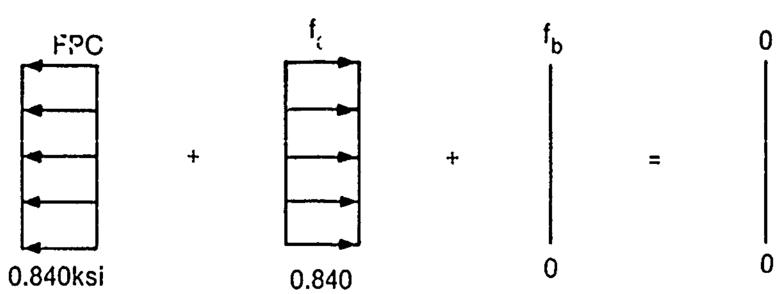
MAX BENDING



$M_{AC} = f_b\ S = (0.7525)(288) = 216.7$ in.-k

TENSION PILES

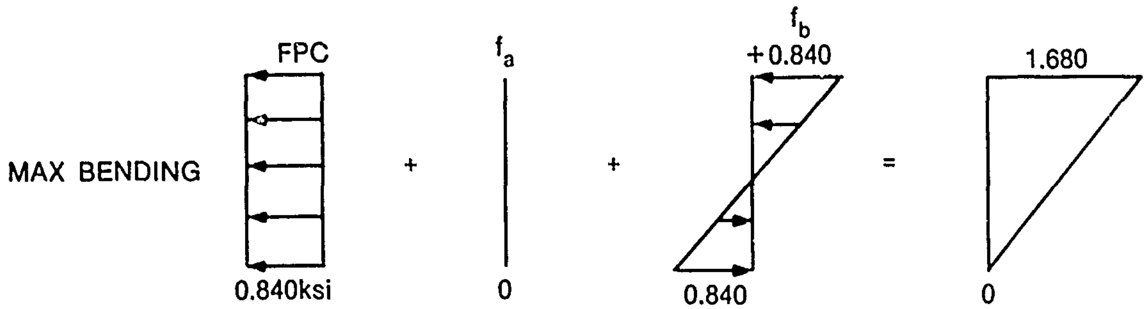
MAX AXIAL



$P_{AT} = f_a\ A = 0.840(144) = 121.0^k$

Allowable stress check (Continued)

Tension piles



$$M_{AT} = f_b S = 0.840\ (288) = 241.9 \text{ in.-kips}$$

E Comp Range

$$\frac{P}{P_{AC}} + \frac{M}{M_{AC}} = 1$$

$$\frac{P}{108.4} + \frac{M}{216.7} = 1$$

E Tension Range

$$\frac{P}{P_{AT}} + \frac{M}{M_{AT}} = 1$$

$$\frac{P}{-121.0} + \frac{M}{242} = 1$$

To determine M_{BA}* and P_{BA}*; solve the following simultaneous equations

$$P_{BA} + \frac{M_{BA}}{2} = 108.4$$

$$-P_{BA} + \frac{M_{BA}}{2} = 121.0$$

$$M_{BA} = 229.4 \text{ in.-k}$$

$$P_{BA} = -6.3^{k}$$

* The simultaneous equations for computing M_{BA} and P_{BA} are only applicable to square piles with a dimension of 12 in.

Stiffness matrix

For details in the development of the stiffness matrix values, refer to Part II, Background Manual.

$$R_1 = \sqrt[4]{\frac{EI_1}{ES}} = \sqrt[4]{\frac{(4{,}074)(1{,}728)}{0.200}}$$

$$R_1 = R_2 = 77.0 \text{ in.}$$

Pile Stiffness Coefficient	C_o Pile Fixity Constant		
$B11 = C_o \dfrac{E_s\sqrt{2}R_2}{2}$	1.0		$1.0\ \dfrac{(0.200)\sqrt{2}(77.0)}{2} = 10.893$
$B22 = C_o \dfrac{E_s\sqrt{2}R_1}{2}$	1.0	Pinned head, Constant E_s	$1.0\ \dfrac{(0.200)\sqrt{2}(77.0)}{2} = 10.893$
$B44 = C_o E_s \sqrt{2} R_1^3$	0		0
$B55 = C_o E_s \sqrt{2} R_2^3$	0		0
$B15 = C_o E_s R_2^2$	0		0
$B24 = -C_o \dfrac{E_s\sqrt{2}R_1}{2}$	0		0

$$B33 = C_{33} \frac{AE_{conc}}{L} = 2.0\ \frac{(144)(4{,}074)}{(60)(12)} = 1{,}629.6$$

B66 = 0 (No torsional effects considered)

Design moment factors:

$$M1 = (KMP1)F2$$

$$M2 = (KMP2)F1$$

$$\left.\begin{aligned} KMP1 &= 0.455R1 \\ KMP2 &= 0.455R2 \end{aligned}\right\} \quad \text{Part II, paragraph 57}$$

$$R1 = \sqrt[4]{\frac{(E)(I1)}{ES}} = \sqrt[4]{\frac{(4,074)(1,728)}{0.200}} = 77.0 \text{ in.}$$

$$R2 = \sqrt[4]{\frac{(E)(I2)}{ES}} = \sqrt[4]{\frac{(4,074)(1,728)}{0.200}} = 77.0 \text{ in.}$$

$$KMP1 = 0.455(77.0) = 35.0 \text{ in.}$$

$$KMP2 = 0.455(77.0) = 35.0 \text{ in.}$$

Load Case Number	PX (KIPS)	PY (KIPS)	PZ (KIPS)	MX (KIP-FT)	MY (KIP-FT)	MZ (KIP-FT)
			Applied Loads - Monolith 135			
1	-40.7	-180.0	204.1	-1,715.7	-3,969.3	-3,908.2
2	-40.7	-180.0	193.6	-1,599.1	-3,920.3	-3,908.2
3	0.0	0.0	252.2	-1,061.6	-5,323.9	0.0
			Applied Loads - Monolith 136			
1	0.0	-66.1	56.3	-564.9	0.0	0.0
2	0.0	-66.1	56.3	-542.0	0.0	0.0
3	0.0	0.0	64.0	-296.3	0.0	0.0

EXAMPLE PROBLEM NO. 2

INPUT TO CPGA (MONOLITH 135)

Data Group	Line No.	
(a)		TITLE
	10	EXAMPLE PROBLEM NO. 2 --
	20	NEW ORLEANS LAKEFRONT LEVEE MONO 135
(b)		PILE PROPERTIES - Omit (Based On Pile Stiffness Matrix Values)
(c)		SOIL DESCRIPTION - Omit (Based On Pile Stiffness Matrix Values)
(d)		FIXITY - Omit (All Piles Are Considered To Be Pinned, Use Default Values)

(e) PILE STIFFNESS

Line No.		B11	B22	B33	B44	B55	B66	B15	B24	LIST
30	BIJ	10.893	10.893	1629.6	0	0	0	0	0	ALL

(f) TENSION PILE STIFFNESS MODIFIER

Line No.		CT	LIST
40	TENSION	0.8	ALL

(g) ALLOWABLE LOADS STEEL AND TIMBER PILES - Omit (Not Applicable)

(h) DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE OR REINFORCED CONCRETE PILES

Line No.		SHAPE	AC	AT	PO	PT	PB	MB	MO	ST	W	LIST
50	DLS	S	80	40	539.4	183.6	73.7	939.0	777.8	H	12	ALL

(i) ALLOWABLE STRESS CHECK - PRESTRESSED CONCRETE PILES

Line No.		SHAPE	A	S	FPC	IPC	FA	FT	LIST
60	ASC	S	144	288	0.840	0.9975	1.750	0	ALL

(j) UNSUPPORTED PILE DATA - Omit (Not Applicable)

(k) DESIGN MOMENT FACTORS FOR PINNED PILE

Line No.		KMP1	KMP2	LIST
70	PMAXMOM	35.0	35.0	ALL

(l) MOMENT FACTORS FOR FIXED UNSUPPORTED PILES - Omit (Not Applicable)

(m) OVERSTRESSED FACTORS - Omit (Default to 1.0)

```
Data    Line
Group   No.

(n)          PILE BATTER
                        BAT       LIST
        80   BATTER     2.0       1 TO 3    5 TO 14
        90   BATTER     3.0         4

(o)          ANGLE TO BATTER DIRECTION
                         ANG         LIST
        100  ANGLE       180         1    8
        110  ANGLE         0         2
        120  ANGLE        90         3  TO  7
        130  ANGLE       270         9  TO  14

(p)          PILE COORDINATES
                    PN1      X1     Y1      Z1     PN2    X2     Y2     Z2
        140  PILE    1       1.5  -1.5      0       8     1.5   -6.5    0

(q)          PILE ROW GENERATION
                 AXIS     NP     PN1     SP1     SP2 ..........................
        150  ROW   X       7      1      5.0     7.0    2 AT 6.25      6.0     4.0
        160  ROW   X       7      8      5.0       4 AT 6.0            5.5

(r)          REPEAT ROWS OF PILES - (Not Used)

(s-x)        Omit (Not Applicable)

(y)          LOAD CASES
                         LCN      PX        PY        PZ        MX         MY          MZ
        170     LOAD      1      -40.7    -180.0     204.1   -1715.7   -3969.3     -3908.2
        180     LOAD      2      -40.7    -180.0     193.6   -1599.1   -3920.3     -3908.2
        190     LOAD      3         0         0      252.2   -1061.6   -5324.9         0

(z)          SPECIFIED CAP DISPLACEMENTS
                              TYPE        D        LIST
        200      DISP          DY        0.0        3
        202      DISP          RX        0.0        3
        204      DISP          RZ        0.0        3

(aa)         OUTPUT AT TERMINAL - Omit (Not Applicable)

(bb)         OUTPUT TO FILE
                              LIST        FPL
        210      FOUT      1 2 3 4 5      X8002

(cc)         PILE STIFFNESS OUTPUT
                              LIST
        220      PSO                   (Default To Pile 1)
```

Data Group	Line No.								
(dd)		PILE CAP DISPLACEMENT OUTPUT							
			X1	Y1	Z1	X2	Y2	Z2	
	230	PCDO	1.5	-1.5	0	36.0	-6.5	0	
(ee)		PILE FORCE OUTPUT							
				LIST					
	240	PFO		ALL					

(ff) PILE COORDINATES OUTPUT - Omit (Default To Print All Pile Locations And Batters)

(gg) PLOT PILE OPTION - Omit (Graphics Not Displayed)

Data File for Problem 2

```
10 EXAMPLE PROBLEM NO. 2-
20 NEW ORLEANS LAKEFRONT LEVEE MONO 135
30 BIJ 10.893 10.893 1629.6 0 0 0 0 0 ALL
40 TENSION 0.8 ALL
50 DLS S 80 40 539.4 183.6 73.7 939.0 777.8 H 12 ALL
60 ASC S 144 288 0.840 0.9975 1.750 0 ALL
70 PMAXMOM 35.0 35.0 ALL
80 BATTER 2.0 1 TO 3 5 TO 14
90 BATTER 3.0 4
100 ANGLE 180 1 8
110 ANGLE 0 2
120 ANGLE 90 3 TO 7
130 ANGLE 270 9 TO 14
140 PILE 1 1.5 -1.5 0 8 1.5 -6.5 0
150 ROW X 7 1 5.0 7.0 2 AT 6.25 6.0 4.0
160 ROW X 7 8 5.0 4 AT 6.0 5.5
170 LOAD 1 -40.7 -180.0 204.1 -1715.7 -3969.3 -3908.2
180 LOAD 2 -40.7 -180.0 193.6 -1599.1 -3920.3 -3908.2
190 LOAD 3   0      0   252.2 -1061.6 -5323.9     0
200 DISP DY 0.0 3
210 DISP RX 0.0 3
220 DISP RZ 0.0 3
230 FOUT 1 2 3 4 5 X8002
240 PSO 1
250 PCDO 1.5 -1.5 0 36.0 -6.5 0
260 PFO ALL
```

<u>Program Execution for Problem 2</u>

```
********************************
*  CORPS PROGRAM *  X0080      *
*    CDC VERSION * 86/09/02-A  *
********************************


CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE  88/04/07   RUN TIME  14.40.07



     FOR PILES WITH UNSUPPORTED HEIGHT:
          A. CPGA CANNOT CALCULATE PMAXMOM FOR NH TYPE SOIL
          B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
             NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
             WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

     ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


 DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
 ENTER F OR I.
? F
 ENTER DATA FILE NAME.
? X80D2

 WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
? N
```

```
                    14 PILES    3 LOAD CASES

 LOAD CASE    1.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   6.

 LOAD CASE    2.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   6.

 LOAD CASE    3.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   0.
 DO YOU WISH TO MODIFY YOUR AXIAL STIFFNESS?
? Y


 TENSION PILE ITERATION.

 LOAD CASE    1.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   6.
                  IT TOOK 1 ITERATIONS.

 LOAD CASE    2.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   6.
                  IT TOOK 1 ITERATIONS.


 CREATING OUTPUT FILE.  PLEASE BE PATIENT.


 SHOULD THE INPUT FILE NAMED 'X80D2   ' BE LISTED? (Y OR N)
? N


 ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
 RUN CPGA AGAIN? (Y OR N)
? N


 THE FOLLOWING FILES WERE GENERATED DURING THIS RUN.

          CPGA OUTPUT FILE IS              X8002
EXIT.
/
```

Listing of Output File Created from CPGA Run for Example 2

```
*******************************
* CORPS PROGRAM # X0080     * CPGA - CASE PILE GROUP ANALYSIS PROGRAM
* VERSION NUMBER # 86/09/02-A * RUN DATE 88/04/07   RUN TIME 14.40.29
*******************************


EXAMPLE PROBLEM NO. 2
NEW ORLEANS LAKEFRONT LEVEE MONO 135


THERE ARE  14 PILES AND
            3 LOAD CASES IN THIS RUN.

ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                                    X          Y          Z
                                  -----      -----      -----
WITH DIAGONAL COORDINATES = (      1.50 ,    -6.50 ,      .00 )
                            (     36.00 ,    -1.50 ,      .00 )


******************************************************************************

         PILE STIFFNESSES AS INPUT


  .10893E+02   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .10893E+02   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .16296E+04   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00


THIS MATRIX APPLIES TO THE FOLLOWING PILES -

    ALL
```

****

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X FT	Y FT	Z FT	BATTER	ANGLE	LENGTH FT	FIXITY
1	1.50	-1.50	.00	2.00	180.00		P
2	6.50	-1.50	.00	2.00	.00		P
3	13.50	-1.50	.00	2.00	90.00		P
4	19.75	-1.50	.00	3.00	90.00		P
5	26.00	-1.50	.00	2.00	90.00		P
6	32.00	-1.50	.00	2.00	90.00		P
7	36.00	-1.50	.00	2.00	90.00		P
8	1.50	-6.50	.00	2.00	180.00		P
9	6.50	-6.50	.00	2.00	270.00		P
10	12.50	-6.50	.00	2.00	270.00		P
11	18.50	-6.50	.00	2.00	270.00		P
12	24.50	-6.50	.00	2.00	270.00		P
13	30.50	-6.50	.00	2.00	270.00		P
14	36.00	-6.50	.00	2.00	270.00		P

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	-40.7	-180.0	204.1	-1715.7	-3969.3	-3908.2
2	-40.7	-180.0	193.6	-1599.1	-3920.3	-3908.2
3	.0	.0	252.2	-1061.6	-5323.9	.0

****

ORIGINAL PILE GROUP STIFFNESS MATRIX

.11237E+04	.10750E-04	-.64748E+03	.50504E+05	-.27194E+05	.44227E+05
.10750E-04	.35518E+04	-.80935E+03	.24766E+06	.48076E+05	.98987E+06
-.64748E+03	-.80935E+03	.18444E+05	-.88045E+06	-.41949E+07	-.98579E+05
.50504E+05	.24766E+06	-.88045E+06	.58628E+08	.19774E+09	.64710E+08
-.27194E+05	.48076E+05	-.41949E+07	.19774E+09	.13221E+10	-.94447E+07
.44227E+05	.98987E+06	-.98579E+05	.64710E+08	-.94447E+07	.32786E+09

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 6.

LOAD CASE 2. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 6.

LOAD CASE 3. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

TENSION PILE ITERATION.

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 6.
IT TOOK 1 ITERATIONS.

LOAD CASE 2. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 6.
IT TOOK 1 ITERATIONS.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	-.4989E-01	-.8753E-01	-.2897E-02	.8779E-04	-.5129E-04	.1009E-03
2	-.5796E-01	-.1063E+00	.5796E-02	.3694E-03	-.6486E-04	.1053E-03
3	.5656E-02	.0000E+00	.1045E-01	.0000E+00	-.1505E-04	.0000E+00

****

DISPLACEMENTS AT DEFINED POINTS

POINT COORDINATE -	X	Y	Z
	FT	FT	FT
	1.50	-1.50	.00

LOAD CASE	DX IN	DY IN	DZ IN
1	-.4807E-01	-.8571E-01	-.3554E-02
2	-.5606E-01	-.1044E+00	.3141E-03
3	.5656E-02	.0000E+00	.1072E-01

POINT COORDINATE -	X	Y	Z
	FT	FT	FT
	36.00	-6.50	.00

LOAD CASE	DX IN	DY IN	DZ IN
1	-.4202E-01	-.4393E-01	.1242E-01
2	-.4975E-01	-.6082E-01	.5000E-02
3	.5656E-02	.0000E+00	.1695E-01

****

EQUIVALENT LOADS FOR SPECIFIED DISPLACEMENTS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
3	.0	-9.2	252.2	-990.9	-5323.9	-53.1

****

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF	ASC	AST	
	K	K	K	IN-K	IN-K	IN-K			KSI	KSI	
1	.5	.9	29.9	32.7	-17.0	.0	.37	.13	1.38	.87	
2	-.5	-.9	-28.6	-30.4	16.3	.0	.71	.55	.96	.48	
3	-.7	.5	-37.0	18.3	24.9	.0	.93	.67	.89	.43	
4	-.7	.5	-16.7	18.3	23.9	.0	.42	.37	1.03	.58	
5	-.6	.5	-19.2	18.3	21.1	.0	.48	.40	1.00	.57	
6	-.5	.5	-10.7	18.3	19.2	.0	.27	.27	1.05	.64	
7	-.5	.5	-5.0	18.3	18.0	.0	.12	.18	1.09	.68	
8	.5	.9	17.8	32.7	-15.8	.0	.22	.17	1.29	.79	
9	.8	-.5	49.7	-16.0	-28.1	.0	.62	.32	1.50	1.03	*
10	.7	-.5	49.8	-16.0	-25.0	.0	.62	.32	1.49	1.04	*
11	.6	-.5	49.9	-16.0	-21.9	.0	.62	.33	1.48	1.05	*
12	.5	-.5	49.9	-16.0	-18.8	.0	.62	.33	1.47	1.07	*
13	.4	-.5	50.0	-16.0	-15.7	.0	.63	.33	1.46	1.08	*
14	.4	-.5	50.1	-16.0	-12.9	.0	.63	.33	1.45	1.09	*

LOAD CASE - 2

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF	ASC	AST	
	K	K	K	IN-K	IN-K	IN-K			KSI	KSI	
1	.5	1.1	41.3	39.8	-19.1	.0	.52	.24	1.49	.92	*
2	-.6	-1.1	-27.8	-37.4	19.8	.0	.69	.57	1.00	.45	
3	-.9	.6	-40.8	21.4	32.1	.0	1.02	.75	.90	.37	
4	-.9	.6	-15.6	21.4	31.2	.0	.39	.38	1.07	.55	
5	-.8	.6	-20.2	21.4	28.4	.0	.51	.44	1.03	.53	
6	-.8	.6	-10.4	21.4	26.6	.0	.26	.29	1.09	.60	
7	-.7	.6	-3.8	21.4	25.4	.0	.09	.19	1.13	.65	
8	.6	1.1	4.4	39.8	-20.7	.0	.06	.29	1.24	.66	
9	1.0	-.5	45.3	-19.0	-36.5	.0	.57	.28	1.50	.96	*
10	.9	-.5	46.6	-19.0	-33.1	.0	.58	.29	1.50	.98	*
11	.8	-.5	47.9	-19.0	-29.7	.0	.60	.30	1.50	1.00	*
12	.8	-.5	49.1	-19.0	[illegible]	.0	.61	.32	1.50	1.02	*
13	.7	-.5	50.4	-19.0	-23.0	.0	.63	.33	1.49	1.04	*
14	.6	-.5	51.6	-19.0	-19.9	.0	.65	.35	1.49	1.06	*

LOAD CASE - 3

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF	ASC	AST	
	K	K	K	IN-K	IN-K	IN-K			KSI	KSI	
1	-.1	.0	11.5	.0	3.8	.0	.14	.14	1.09	.91	*
2	.0	.0	21.1	.0	.1	.0	.26	.11	1.14	.99	*
3	-.1	-.1	18.8	-2.2	2.2	.0	.23	.13	1.14	.96	*
4	.0	-.1	21.7	-2.2	1.7	.0	.27	.12	1.16	.98	*
5	-.1	-.1	22.1	-2.2	2.6	.0	.28	.12	1.17	.98	*
6	-.1	-.1	23.7	-2.2	2.8	.0	.30	.12	1.18	.99	*
7	-.1	-.1	24.7	-2.2	2.9	.0	.31	.11	1.19	.99	*
8	-.1	.0	11.5	.0	3.8	.0	.14	.14	1.09	.91	*
9	-.1	.1	16.9	2.2	2.0	.0	.21	.13	1.13	.94	*
10	-.1	.1	18.5	2.2	2.2	.0	.23	.13	1.14	.95	*
11	-.1	.1	20.1	2.2	2.4	.0	.25	.13	1.15	.96	*
12	-.1	.1	21.7	2.2	2.5	.0	.27	.12	1.16	.97	*
13	-.1	.1	23.3	2.2	2.7	.0	.29	.12	1.18	.98	*
14	-.1	.1	24.7	2.2	2.9	.0	.31	.11	1.19	.99	*

Specified Pile Cap Displacements

In Load Case 3, DY , RX , and RZ are specified as 0. This means that the monolith is restrained from movement in these three directions. As a result, the applied loads are modified as shown under output "Equivalent Loads for Specified Displacements."

	PX	PY	PZ	MX	MY	MZ
Applied loads	0	0	252.2^{k}	$-1,051.6^{ft\text{-}kips}$	$-5,323.9^{ft\text{-}kips}$	0
Equivalent loads for specified displacements	0	-9.2^{k}	252.2^{k}	$-990.9^{ft\text{-}kips}$	$-5,323.9^{ft\text{-}kips}$	$-53.1^{ft\text{-}kips}$

Under the applied loads, the monolith attempts to displace in the DY , RX , and RZ mode. However, since it is restrained from doing so, the equivalent loads represent the loads applied to the monolith to produce the specified displacements DY , RX , and RZ and the computed displacements DX , DZ , and RY from the applied loads. The difference between the applied loads and equivalent loads represent the additional loads that are placed on the monolith to produce the specified displacements.

	PY	MX	MZ
Difference	-9.2^{k}	$70.7^{ft\text{-}kips}$	$-53.1^{ft\text{-}kips}$

A check of CPGA output for Monolith 135, Case 1, P[illegible]e 1, by referring to Part I, User's Manual is shown:

Part I, paragraph 24k

$$M2 = (KMP2)(-F1) = (35.0)(-0.5) = -17.5 \text{ kip-in.}$$

-17.0 kip-in. from output -ok- difference due to roundoff of F1

$$M1 = (KMP1)(F2) = (35.0)(0.9) = 31.5 \text{ kip-in.}$$

32.7 kip-in. from output ok-diff due to roundoff

Part I, Equation 1

$$ALF = \frac{F3}{AC}\left(\frac{1}{OSF}\right) = \frac{29.9}{80}\left(\frac{1}{1.0}\right) = 0.3738$$

0.37 from output - ok

Check CBF

$$\frac{PB}{SF} = \frac{73.7}{2.7} = 27.3$$

$$F3 = 29.9$$

$$F3 > \frac{PB}{SF} \text{ ... use Part I, Equation 7}$$

Part I, Equation 7

$$CBF = \left[\frac{(SF)(F3) - PB}{PO - PB} + SF(MF1)(\overline{M1}^2 + \overline{M2}^2)^{1/2}\left(\frac{1}{(K)(MB)}\right)\right]\frac{1}{OSF}$$

Compute K

Part I, paragraph 24h

$$A = \tan^{-1}\left|\frac{M2}{M1}\right| = \tan^{-1}\frac{17.0}{32.7} = 27.46°$$

$$K = 1 - \left(\frac{A}{45}\right)(0.15) = 1 - \left(\frac{27.46}{45}\right)(0.15) = 0.908$$

$$(\overline{M1}^2 + \overline{M2}^2)^{1/2} = (\overline{32.7}^2 + \overline{17.0}^2)^{1/2} = 36.85 > (EMIN)(F3) = (1.2)(29.9) = 35.9$$

$$\therefore \quad \text{use } (\overline{M1}^2 + \overline{M2}^2)^{1/2}$$

$$CBF = \left[\frac{(2.7)(29.9) - 73.7}{539.4 - 73.7} + (2.7)(1.0)(36.85)\frac{1}{(0.908)(939.0)}\right]\frac{1}{1.0}$$

$$= \frac{80.7 - 73.7}{539.4 - 73.7} + 0.117 = \frac{7.0}{465.7} + 0.117 = 0.015 + 0.117$$

$$= 0.132$$

0.13 from output - ok

Allowable stress check, Part I, User's Manual:

Maximum compressive stress, Case 1, Pile 1

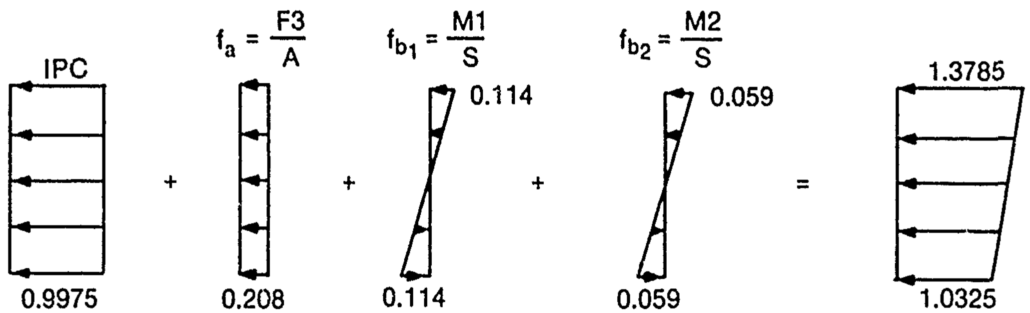
Equation 11:

$$ASC = \frac{1}{OSF}\left[\left(\frac{F3}{A}\right) + \frac{(MF1)\,|M1|}{S} + \frac{(MF2)\,|M2|}{S}\right] + IPC$$

$$= \frac{1}{1.0}\left[\frac{29.9}{144} + \frac{1.0(32.7)}{288} + \frac{1.0(17.0)}{288}\right] + 0.9975$$

$$= 0.208 + 0.114 + 0.059 + 0.9975 = 1.3785$$

1.38 from output - ok



Maximum tensile stress, Case 1, Pile 1

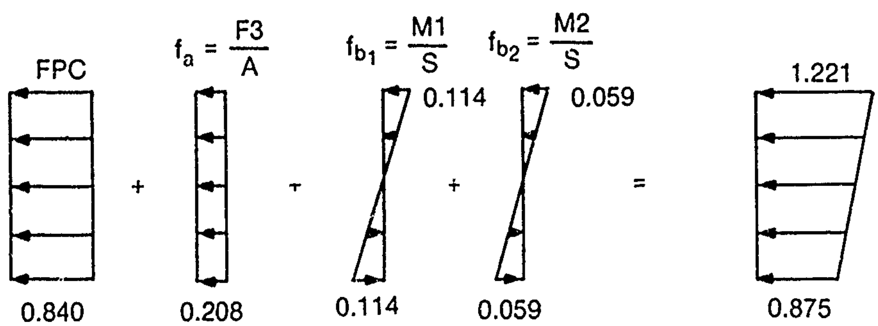
Part I
Equation 10

$$AST = \frac{1}{OSFT}\left[\left(\frac{F3}{A}\right) - \frac{(MF1)\,|M1|}{S} - \frac{(MF2)\,|M2|}{S}\right] + FPC$$

$$= \frac{1}{1.0}\left[\frac{29.9}{144} - \frac{1.0(32.7)}{288} - \frac{1.0(17.0)}{288}\right] + 0.840$$

$$= 0.208 - 0.114 - 0.059 + 0.840 = 0.875$$

0.87 from output - ok



Monolith 135, Case 1, Pile 2

Part I, paragraphs 24k and 1:

$$\left\{\begin{array}{l} M2 = (KMP2)(-F1) = (35.0)[-(-0.5)] = 17.5 \text{ kip-in.} \\ \qquad\text{16.3 kip-in. from output -ok- difference due to roundoff of F1} \\ M1 = (KMP1)(F2) = (35.0)(-0.9) = -31.5 \text{ kip-in.} \\ \qquad\text{-30.4 kip-in. from output ok-diff due to roundoff} \end{array}\right.$$

Part I, Equation 2:

$$ALF = \left(\frac{-F3}{AT}\right)\left(\frac{1}{OSF}\right) = \frac{-(-28.6)}{40}\left(\frac{1}{1.0}\right) = 0.715$$

0.71 from output - ok

Check CBF

$$F3 < 0$$

Part I, Equation 9:

$$CBF = \left[SF\left(\frac{-F3}{PT}\right) + \frac{SF(\overline{M1}^2 + \overline{M2}^2)^{1/2}}{K(MO)}\right]\frac{1}{OSFT}$$

Compute K

$$A = \tan^{-1}\frac{|M2|}{|M1|} = \tan^{-1}\frac{16.3}{30.4} = 28.20°$$

$$K = 1 - \left(\frac{A}{45}\right)(0.15) = 1 - \left(\frac{28.20}{45}\right)(0.15)$$

$$K = 0.906$$

$$CBF = \left\{2.7\left[\frac{-(-28.6)}{183.6}\right] + \frac{2.7(\overline{30.4}^2 + \overline{16.3}^2)^{1/2}}{(0.906)(777.8)}\right\}\frac{1}{1.0}$$

$$= 0.421 + 0.132$$

$$= 0.553$$

0.55 from output - ok

Allowable stress check, Part I, User's Manual, paragraph 24i

Maximum compressive stress, Case 1, Pile 2:

Part I, Equation 11:

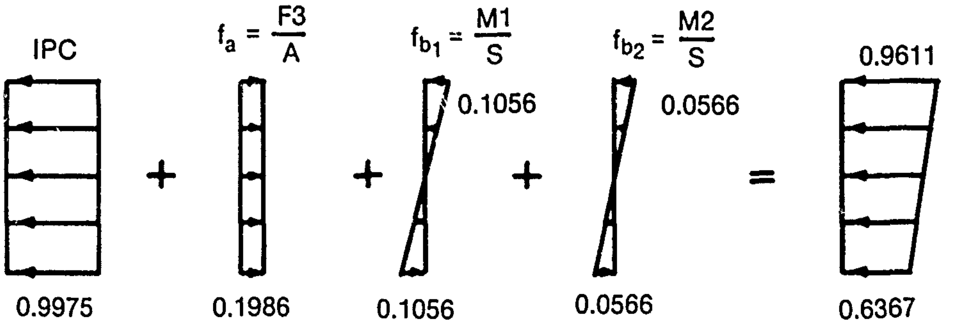
$$ASC = \frac{1}{OSF}\left[\left(\frac{F3}{A}\right) + \frac{(MF1)\,|M1|}{S} + \frac{(MF2)\,|M2|}{S}\right] + IPC$$

$$= \frac{1}{1.0}\left[\frac{-28.6}{144} + \frac{1.0(30.4)}{288} + \frac{1.0(16.3)}{288}\right] + 0.9975$$

$$= -0.1986 + 0.1056 + 0.0566 + 0.9975$$

$$= 0.9611$$

0.96 from output - ok



Maximum tensile stress, Case 1, Pile 2:

Part II Equation 14:

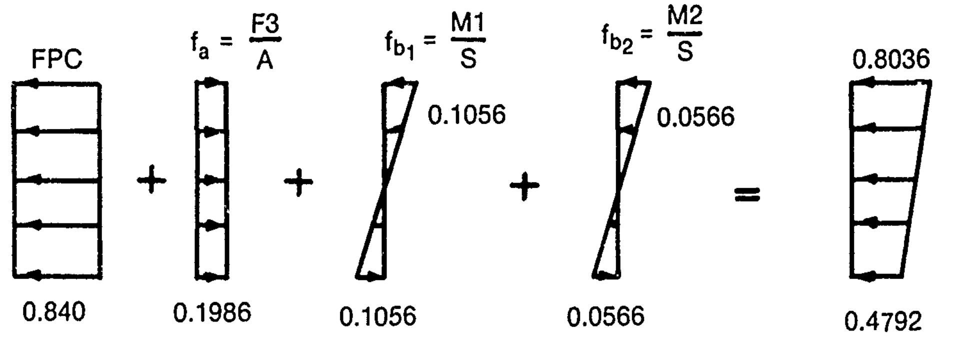
$$AST = \frac{1}{OSFT}\left[\left(\frac{F3}{A}\right) - \frac{(MF1)\,|M1|}{S} - \frac{(MF2)\,|M2|}{S}\right] + FPC$$

$$= \frac{1}{1.0}\left[\frac{-28.6}{144} - \frac{1.0(30.4)}{288} - \frac{1.0(16.3)}{288}\right] + 0.840$$

$$= -0.1986 - 0.1056 - 0.0566 + 0.840$$

$$= 0.4792$$

0.48 from output - ok



EXAMPLE PROBLEM NO. 2A

INPUT TO CPGA (MONOLITH 136)

Data Group	Line No.								
(a)		TITLE							
	10	EXAMPLE PROBLEM NO. 2A -							
	20	NEW ORLEANS LAKEFRONT LEVEE MONO 136							

DATA GROUPS (2) THROUGH (13) AND LINE NUMBERS 30 THROUGH 70 ARE IDENTICAL TO INPUT FOR MONOLITH 135

Data Group	Line No.								
(n)		PILE BATTER							
			BAT	LIST					
	80	BATTER	2.0	ALL					
(o)		ANGLE TO BATTER DIRECTION							
			ANG	LIST					
	90	ANGLE	90	1 2					
	100	ANGLE	270	3 4					
(p)		PILE COORDINATES							
			PN1	X1	Y1	Z1	PN2	X2	Y2	Z2
	110	PILE	1	-4.0	-1.5	0	2	4.0	-1.5	0
			PN3	X3	Y3	Z3	PN4	X4	Y4	Z4
	120	PILE	3	-4.0	-6.5	0	4	4.0	-6.5	0

(q) PILE ROW GENERATION - Omit (Not Used)

(r) REPEAT ROWS OF PILES - Omit (Not Used)

(s) - (x) Omit (Not Applicable)

Data Group	Line No.								
(y)		LOAD CASES							
			LCN	PX	PY	PZ	MX	MY	MZ
	130	LOAD	1	0	-66.1	56.3	-564.9	0	0
	140	LOAD	2	0	-66.1	56.3	-542.0	0	0
	150	LOAD	3	0	0	64.0	-296.3	0	0

(z) SPECIFIED CAP DISPLACEMENTS - Omit (Not Desired)

(aa) OUTPUT AT TERMINAL - Omit (Not Applicable)

(bb) OUTPUT TO PILE

		LIST	FPL
160	FOUT	1 2 3 4 5	X8002A

(cc) PILE STIFFNESS OUTPUT

		LIST	
170	PSO		(Default To Pile 1)

(dd) PILE CAP DISPLACEMENT OUTPUT - Omit (Not Desired)

(ee) PILE FORCE OUTPUT

		LIST
180	PFO	ALL

(ff) PILE COORDINATES OUTPUT - Omit (Default To Print All Pile Locations And Batters)

(gg) PLOT PILE OPTION - Omit (Graphics Not Displayed)

<u>List of Data File for Problem 2A</u>

```
10 EXAMPLE PROBLEM NO. 2A-
20 NEW ORLEANS LAKEFRONT LEVEE MONO 136
30 BIJ 10.893 10.893 1629.6 0 0 0 0 0 ALL
40 TENSION 0.8 ALL
50 DLS S 80 40 539.4 183.6 73.7 939.0 777.8 H 12 ALL
60 ASC S 144 288 0.840 0.9975 1.750 0 ALL
70 PMAXMOM 35.0 35.0 ALL
80 BATTER 2.0 ALL
120 ANGLE 90 1 2
130 ANGLE 270 3 4
140 PILE 1 -4.0 -1.5 0 2 4.0 -1.5 0
150 PILE 3 -4.0 -6.5 0 4 4.0 -6.5 0
170 LOAD 1 0 -66.1 56.3 -564.9 0 0
180 LOAD 2 0 -66.1 56.3 -542.0 0 0
190 LOAD 3   0      0   64.0 -296.3 0 0
230 FOUT 1 2 3 4 5 X8002A
240 PSO
260 PFO ALL
```

Execution of Problem 2A

```
********************************
*  CORPS PROGRAM *  X0080      *
*   CDC VERSION * 86/09/02-A  *
********************************


CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE  88/04/07   RUN TIME  16.07.59


     FOR PILES WITH UNSUPPORTED HEIGHT:
          A. CPGA CANNOT CALCULATE PMAXIMUM FOR NH TYPE SOIL
          B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
             NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
             WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

     ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


 DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
 ENTER F OR I.
? F
 ENTER DATA FILE NAME.
? X80D2A

 WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
? N


                       4 PILES    3 LOAD CASES

 LOAD CASE    1.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   2.

 LOAD CASE    2.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   2.

 LOAD CASE    3.  NUMBER OF FAILURES =   0.  NUMBER OF PILES IN TENSION =   0.
```

```
DO YOU WISH TO MODIFY YOUR AXIAL STIFFNESS?
? Y


TENSION PILE ITERATION.

LOAD CASE     1. NUMBER OF FAILURES =   0. NUMBER OF PILES IN TENSION =   2.
                 IT TOOK 1 ITERATIONS.

LOAD CASE     2. NUMBER OF FAILURES =   0. NUMBER OF PILES IN TENSION =   2.
                 IT TOOK 1 ITERATIONS.


CREATING OUTPUT FILE.  PLEASE BE PATIENT.


SHOULD THE INPUT FILE NAMED 'X80D2A ' BE LISTED? (Y OR N)
? N


ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
 RUN CPGA AGAIN? (Y OR N)
? N


THE FOLLOWING FILES WERE GENERATED DURING THIS RUN.

         CPGA OUTPUT FILE IS              X8002A
EXIT.
```

Listing of Output File Created from CPGA Run for Example 2A

```
********************************
* CORPS PROGRAM  *  X0080     *  CPGA - CASE PILE GROUP ANALYSIS PROGRAM
* VERSION NUMBER * 86/09/02-A *  RUN DATE  88/04/07   RUN TIME  16.08.06
********************************


EXAMPLE PROBLEM NO. 2A
NEW ORLEANS LAKEFRONT LEVEE MONO 136


THERE ARE   4 PILES AND
            3 LOAD CASES IN THIS RUN.

ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                                            X          Y          Z
                                          -----      -----      -----
WITH DIAGONAL COORDINATES = (            -4.00 ,    -6.50 ,      .00 )
                            (             4.00 ,    -1.50 ,      .00 )


********************************************************************************

         PILE STIFFNESSES AS INPUT


  .10893E+02   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .10893E+02   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .16296E+04   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00
  .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00

THIS MATRIX APPLIES TO THE FOLLOWING PILES -

    ALL


********************************************************************************

         PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM        X          Y          Z      BATTER   ANGLE   LENGTH  FIXITY
           FT         FT         FT                        FT

  1      -4.00      -1.50       .00      2.00    90.00              P
  2       4.00      -1.50       .00      2.00    90.00              P
  3      -4.00      -6.50       .00      2.00   270.00              P
  4       4.00      -6.50       .00      2.00   270.00              P
```

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	.0	-66.1	56.3	-564.9	.0	.0
2	.0	-66.1	56.3	-542.0	.0	.0
3	.0	.0	64.0	-296.3	.0	.0

****

ORIGINAL PILE GROUP STIFFNESS MATRIX

.43572E+02	.46487E-05	-.46487E-05	.50206E-03	.00000E+00	.20915E+04
.46487E-05	.13385E+04	-.36380E-11	.77698E+05	.00000E+00	.29287E-03
-.46487E-05	.00000E+00	.52234E+04	-.25072E+06	.00000E+00	-.50206E-03
.50206E-03	.77698E+05	-.25072E+06	.16736E+08	.00000E+00	.41671E-01
.00000E+00	.00000E+00	.00000E+00	.00000E+00	.12035E+08	.74506E-08
.20915E+04	.29287E-03	-.50206E-03	.41671E-01	.22352E-07	.32236E+07

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 2.

LOAD CASE 2. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 2.

LOAD CASE 3. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

TENSION PILE ITERATION.

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 2.
IT TOOK 1 ITERATIONS.

LOAD CASE 2. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 2.
IT TOOK 1 ITERATIONS.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	.6565E-08	.2266E-01	-.5373E-01	-.1305E-02	-.1317E-12	.2374E-11
2	.6268E-08	-.6080E-01	.1574E-01	.1391E-03	-.1278E-12	.2304E-11
3	.1777E-08	.1470E+00	-.1093E+00	-.2532E-02	-.7458E-27	.1205E-11

****

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF	ASC KSI	AST KSI	
1	.4	.0	-22.1	.0	-12.9	.0	.55	.37	.89	.64	
2	.4	.0	-22.1	.0	-12.9	.0	.55	.37	.89	.64	
3	-.5	.0	53.5	.0	15.9	.0	.67	.34	1.42	1.16	#
4	-.5	.0	53.5	.0	15.9	.0	.67	.34	1.42	1.16	#

LOAD CASE - 2

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF	ASC KSI	AST KSI	
1	-.7	.0	-20.0	.0	23.0	.0	.50	.37	.94	.62	
2	-.7	.0	-20.0	.0	23.0	.0	.50	.37	.94	.62	
3	.6	.0	51.4	.0	-19.9	.0	.64	.32	1.42	1.13	#
4	.6	.0	51.4	.0	-19.9	.0	.64	.32	1.42	1.13	#

LOAD CASE - 3

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF	ASC KSI	AST KSI
1	1.7	.0	14.3	.0	-61.0	.0	.18	.26	1.31	.73
2	1.7	.0	14.3	.0	-61.0	.0	.18	.26	1.31	.73
3	-1.9	.0	21.5	.0	65.2	.0	.27	.22	1.37	.76
4	-1.9	.0	21.5	[illegible]	65.2	.0	.27	.22	1.37	.76

Example Problem 2A

Check CPGA output, Monolith 136, Case 1, Pile 1:

Part I, paragraph 24k:

$$M2 = (KMP2)(-F1) = (35.0)(-0.4) = -14.0 \text{ kip-in.}$$

-12.9 kip-in. from output -ok- difference due to roundoff of F1

$$M1 = (KMP1)(F2) = 35.0(0) = 0$$

0 from output

Part I, Equation 2:

$$ALF = \frac{-F3}{AT}\left(\frac{1}{OSFT}\right) = \left[\frac{-(-22.1)}{40}\right]\frac{1}{1.0} = 0.5525$$

0.55 from output - ok

Check CBF

$$F3 < 0$$

Part I, Equation 9:

$$CBF = \left[SF\left(\frac{-F3}{PT}\right) + \frac{SF(\overline{M1}^2 + \overline{M2}^2)^{1/2}}{K(MO)}\right]\frac{1}{OSFT}$$

Compute K

$$A = \tan^{-1}\left|\frac{M1}{M2}\right| = \tan^{-1}\frac{0}{12.9} = 0$$

$$K = 1 - \frac{A}{45}(0.15) = 1 - \frac{0}{45}(0.15) = 1.0$$

$$CBF = \left\{2.7\left[\frac{-(-22.1)}{183.6}\right] + \frac{2.7\left[\overline{0}^2 + (-12.9^2)\right]^{1/2}}{1.0(777.8)}\right\}\frac{1}{1.0}$$

$$= 0.325 + 0.045$$

$$= 0.370$$

0.37 from output - ok

Allowable stress check, Part I, User's Manual, paragraph 24i

Maximum compressive stress, Case 1, Pile 1:

Part I, Equation 11:

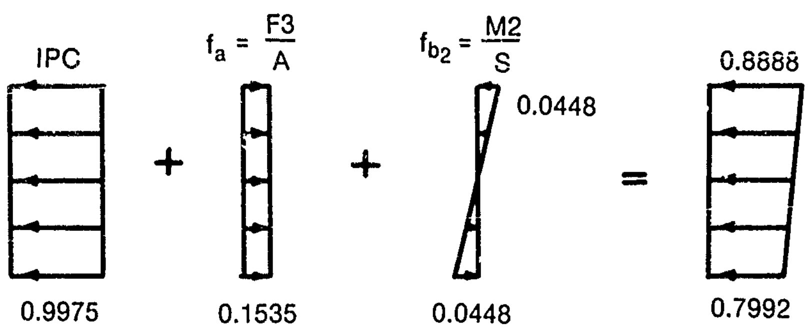
$$ASC = \frac{1}{OSF}\left[\left(\frac{F3}{A}\right) + \frac{(MF1)\,|M1|}{S} + \frac{(MF2)\,|M2|}{S}\right] + IPC$$

$$= \frac{1}{1.0}\left[\frac{-22.1}{144} + 0 + \frac{1.0(12.9)}{288}\right] + 0.9975$$

$$= -0.1535 + 0.0448 + 0.9975$$

$$= 0.8888$$

0.89 from output - ok



Maximum tensile stress, Case 1, Pile 1:

Part I Equation 10:

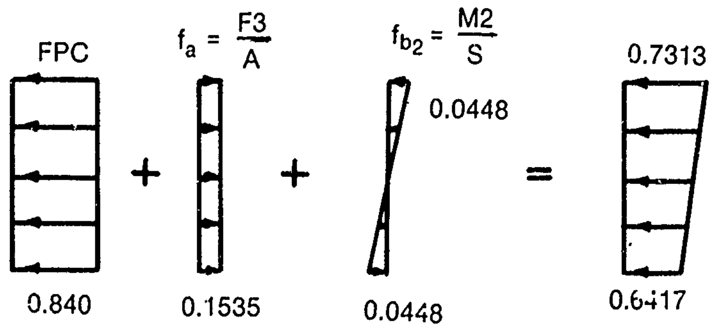
$$AST = \frac{1}{OSFT}\left[\left(\frac{F3}{A}\right) - \frac{(MF1)\,|M1|}{S} - \frac{(MF2)\,|M2|}{S}\right] + FPC$$

$$= \frac{1}{1.0}\left[\frac{-22.1}{144} - 0 - \frac{1.0(12.9)}{288}\right] + 0.840$$

$$= -0.1535 - 0.0448 + 0.840$$

$$= 0.6417$$

0.64 from output - ok



Monolith 136, Case 1, Pile 3:

Part I, paragraph 24k:

$$M2 = (KMP2)(-F1) = (35.0)[-(-0.5)] = 17.5 \text{ kip-in.}$$

15.9 kip-in. from output -ok- difference due to roundoff

$$M1 = KMP1(F2) = 35.0(0) = 0$$

0 from output

Part I, Equation 1:

$$ALF = \frac{F3}{AC}\left(\frac{1}{OSF}\right) = \frac{53.5}{80}\left(\frac{1}{1.0}\right) = 0.669$$

0.67 from output - ok

Check CBF

$$\frac{PB}{SF} = \frac{73.7}{2.7} = 27.3$$

$$F3 = 53.5$$

$$F3 > \frac{PB}{SF} \therefore \text{ use Part I, Equation 7}$$

Part I, Equation 7:

$$CBF = \left\{\frac{(SF)(F3) - PB}{PO - PB} + SF(MF1)(\overline{M1}^2 + \overline{M2}^2)^{1/2}\left[\frac{1}{(K)(MB)}\right]\right\}\frac{1}{OSF}$$

Compute K

Part I, paragraph 24h:

$$A = \tan^{-1}\frac{|M1|}{|M2|} = \tan^{-1}\frac{0}{15.9} = 0$$

$$K = 1 - \left(\frac{A}{45}\right)(0.15) = 1 - \frac{0}{45}(0.15) = 1.0$$

$$(\overline{M1}^2 + \overline{M2}^2)^{1/2} = (\overline{0}^2 + \overline{15.9}^2)^{1/2} = 15.9 < (EMIN)(F3) = (1.2)(53.5) = 64.2$$

$\therefore$ use (EMIN)(F3) in place of $(\overline{M1}^2 + \overline{M2}^2)^{1/2}$ in Part I, Equation 7

$$CBF = \left\{\frac{(2.7)(53.5) - 73.7}{539.4 - 73.7} + (2.7)(1.0)(64.2)\left[\frac{1}{(1.0)(939.0)}\right]\right\}\frac{1}{1.0}$$

$$= \frac{144.45 - 73.7}{465.7} + 0.185 = \frac{70.75}{465.7} + 0.185$$

$$= 0.152 + 0.185$$

$$= 0.337$$

0.34 from output - ok

Allowable stress check, Part I, User's Manual, paragraph 24i

Maximum compressive stress, Case 1, Pile 3:

Part I,
Equation 11:

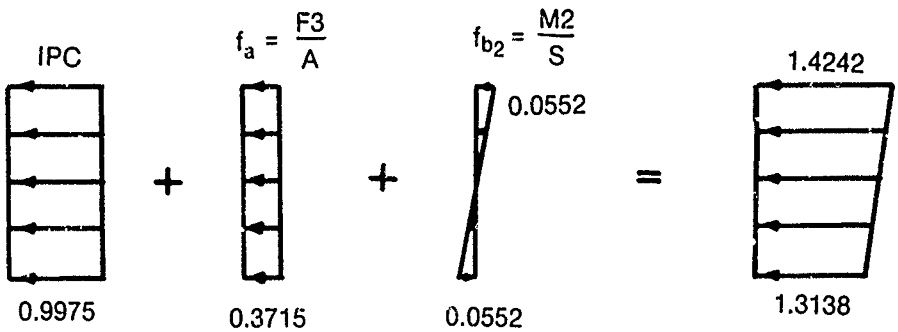
$$ASC = \frac{1}{OSF}\left[\left(\frac{F3}{A}\right) + \frac{(MF1)\,|M1|}{S} + \frac{(MF2)\,|M2|}{S}\right] + IPC$$

$$= \frac{1}{1.0}\left[\frac{53.5}{144} + 0 + \frac{1.0(15.9)}{288}\right] + 0.9975$$

$$= 0.3715 + 0.0552 + 0.9975$$

$$= 1.4242$$

1.42 from output - ok



Maximum tensile stress, Case 1, Pile 3:

Part I
Equation 10:

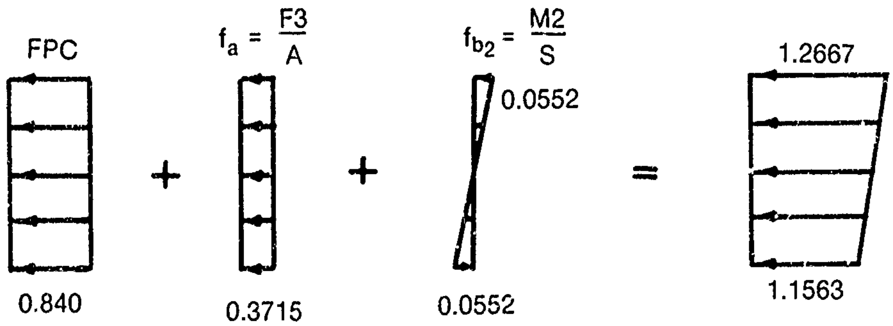
$$AST = \frac{1}{OSFT}\left[\left(\frac{F3}{A}\right) - \frac{(MF1)\,|M1|}{S} - \frac{(MF2)\,|M2|}{S}\right] + FPC$$

$$= \frac{1}{1.0}\left[\frac{53.5}{144} - 0 - \frac{1.0(15.9)}{288}\right] + 0.840$$

$$= 0.3715 - 0.0552 + 0.840$$

$$= 1.1563$$

1.16 from output - ok



Example Problem 3, A Three-Dimensional Massive Foundation with Linearly Varying Soil Modulus

11. This problem is the Old River Low Sill Control Structure located in the New Orleans District. The structure was designed by the Mississippi River Commission in 1955 using the Culmann method.

12. The foundation shown in Figures B9 and B10 contains 240 piles. The piles are steel H , 90 ft long, and are assumed to act as end bearing in a medium dense sand. The medium sand has a linearly varying E_s , with NH equal to 19 pci. Pile heads are assumed pinned. Allowable pile capacities are 200 kips in compression and 80 kips in tension.

13. This problem illustrates the generation of pile coordinates in three dimensions for a massive foundation with a sloping base. It also gives evidence of how the properties of steel H piles are input.

14. Computations necessa', for determining input items to the CPGA program are shown along with input and output from the program.

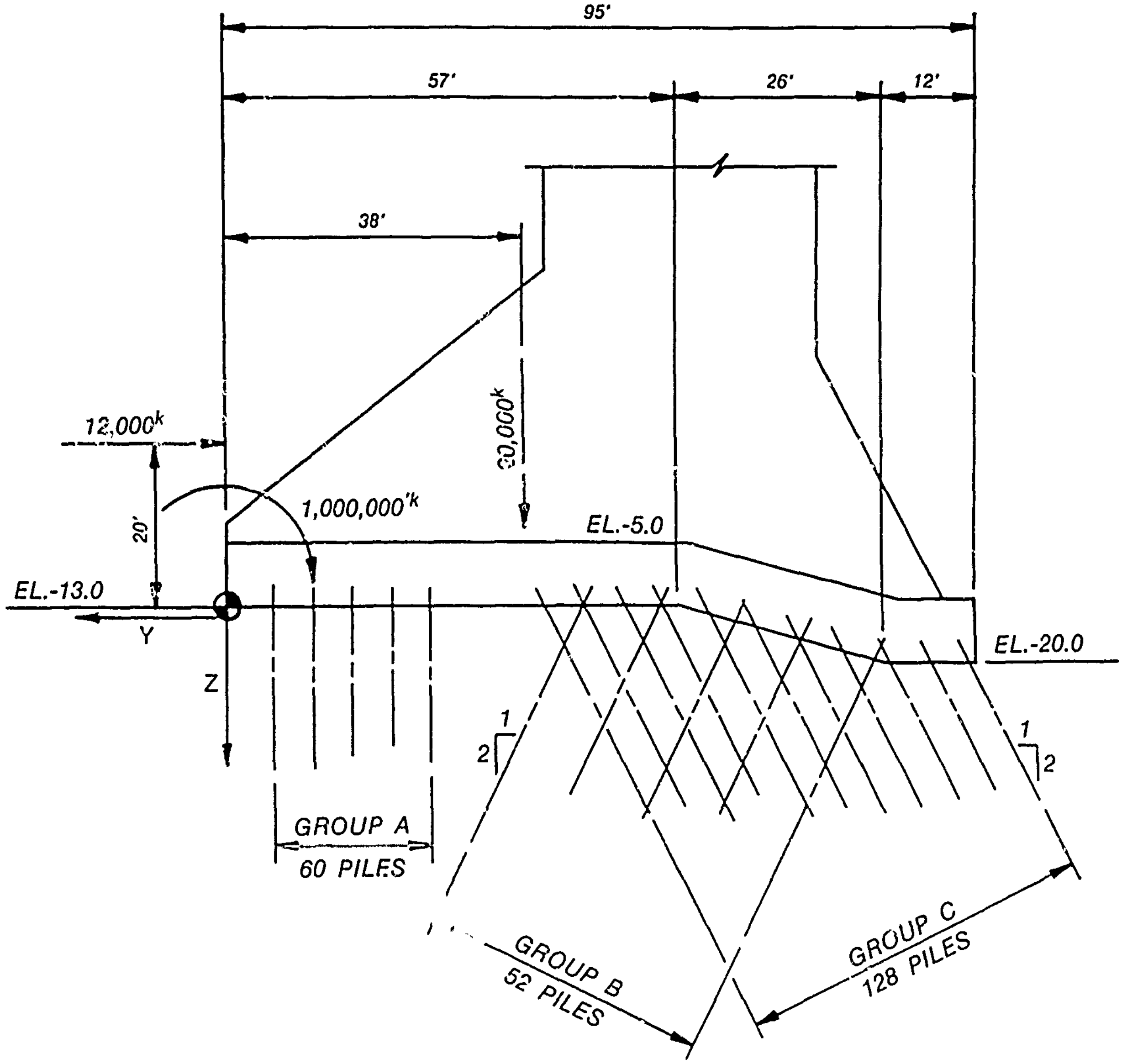


Figure B9. Pile arrangement for Example Problem 3

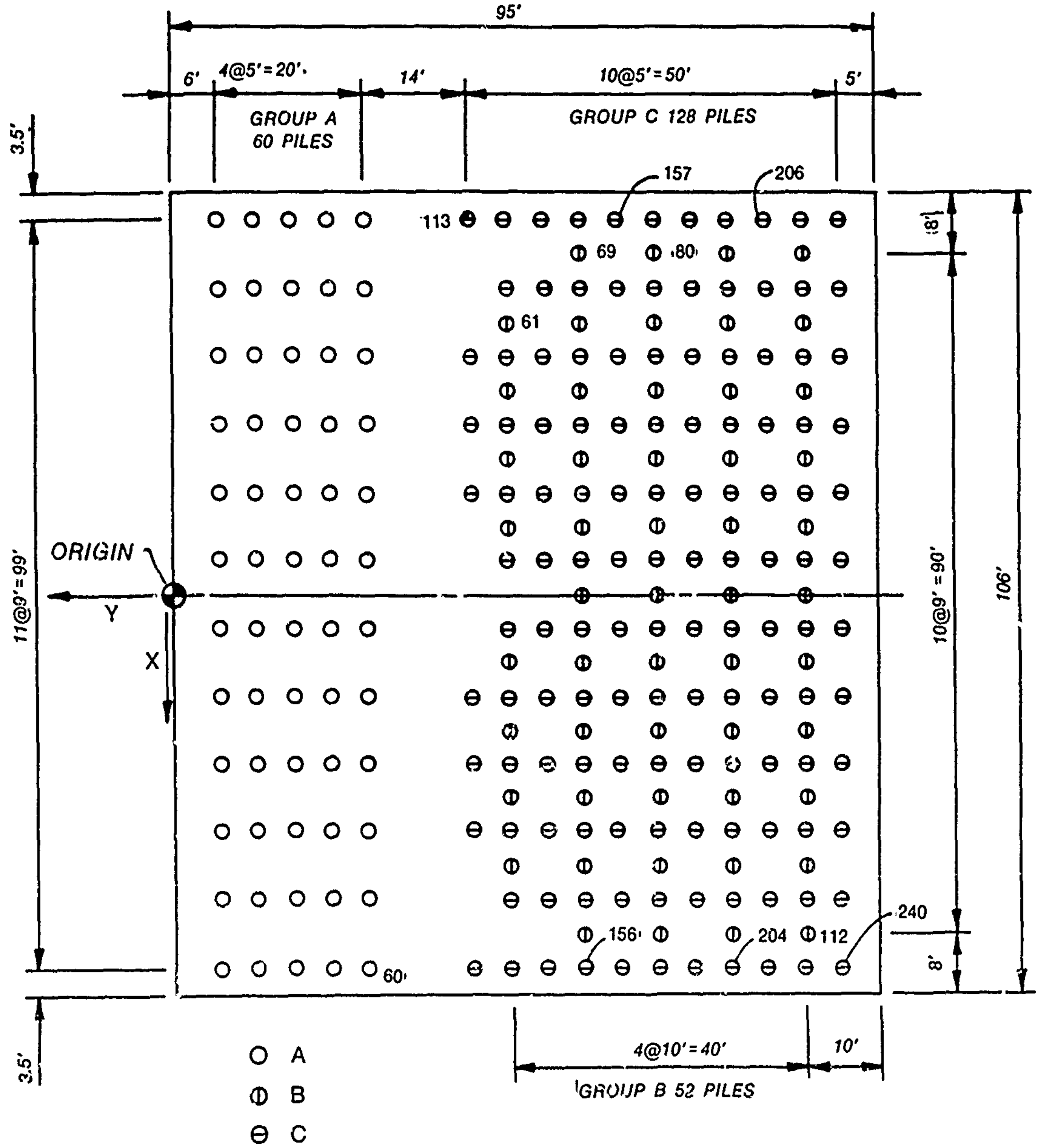


Figure B10. Pile layout indicating location at El 13.0*

---

* All elevations (El) cited herein are in feet referred to National Geodetic Datum (NGVD) of 1929.

Massive foundation (linearly varying ES Old River Low Sill Control Structure for Example Problem 3)

Piles HP 14 × 73:

Properties	
$E = 29{,}000$ ksi	$NH = 0.019\ \text{k/in}^3$
$I1 = 261\ \text{in}^4$	(medium sand)
$S1 = 35.8\ \text{in}^3$	Fixity = pinned
$I2 = 729\ \text{in}^4$	$C33 = 1.0$
$S2 = 107\ \text{in}^3$	$B66 = 0.0$
$A = 21.4\ \text{in}^2$	
$L = 90.0$ ft	

Allowables

$$AC = 200^k < \overset{\text{Allow compr @ pile tip}}{10.0(21.4)}$$

$$AT = 80$$

$$ACC = (F_{ac})(A) = (\overset{\text{(TR K-80-5)}}{17.0})(21.4) = 363.8^k$$

$$ATT = (F_{at})(A) = (18.0)(21.4) = 385.2^k$$

$$AM1 = (F_b)(S1) = (18.0)(35.8) = 644.4 \text{ in-kips}$$

$$AM2 = (F_b)(S2) = (18.0)(107) = 1{,}926 \text{ in-kips}$$

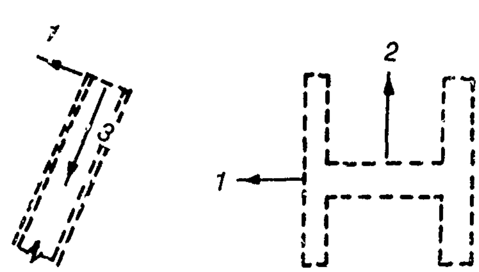


Figure B11. Pile orientation local coordinate system

Design Moment Factors

$$M1 = (KMP1)(F2)$$

$$M2 = (KMP2)(F1)$$

$$\left.\begin{aligned} KMP1 &= 0.772\ T1 \\ KMP2 &= 0.772\ T2 \end{aligned}\right\}$$ Part II, Background Manual, paragraph 57

$$T1 = \sqrt[5]{\frac{(E)(I1)}{NH}} = \sqrt[5]{\frac{(29{,}000)(261)}{(0.019)}} = 52.5 \text{ in.}$$

$$T2 = \sqrt[5]{\frac{(E)(I2)}{NH}} = \sqrt[5]{\frac{(29{,}000)(729)}{(0.019)}} = 64.5 \text{ in.}$$

$$KMP1 = (0.772)(52.5) = 40.5 \text{ in.}$$

$$KMP2 = (0.772)(64.5) = 49.8 \text{ in.}$$

Load Case Number	PX (KIPS)	PY (KIPS)	PZ (KIPS)	MX (KIP-FT)	MY (KIP-FT)	MZ (KIP-FT)
1	0	-12,000	20,000	-1,000,000	0	0

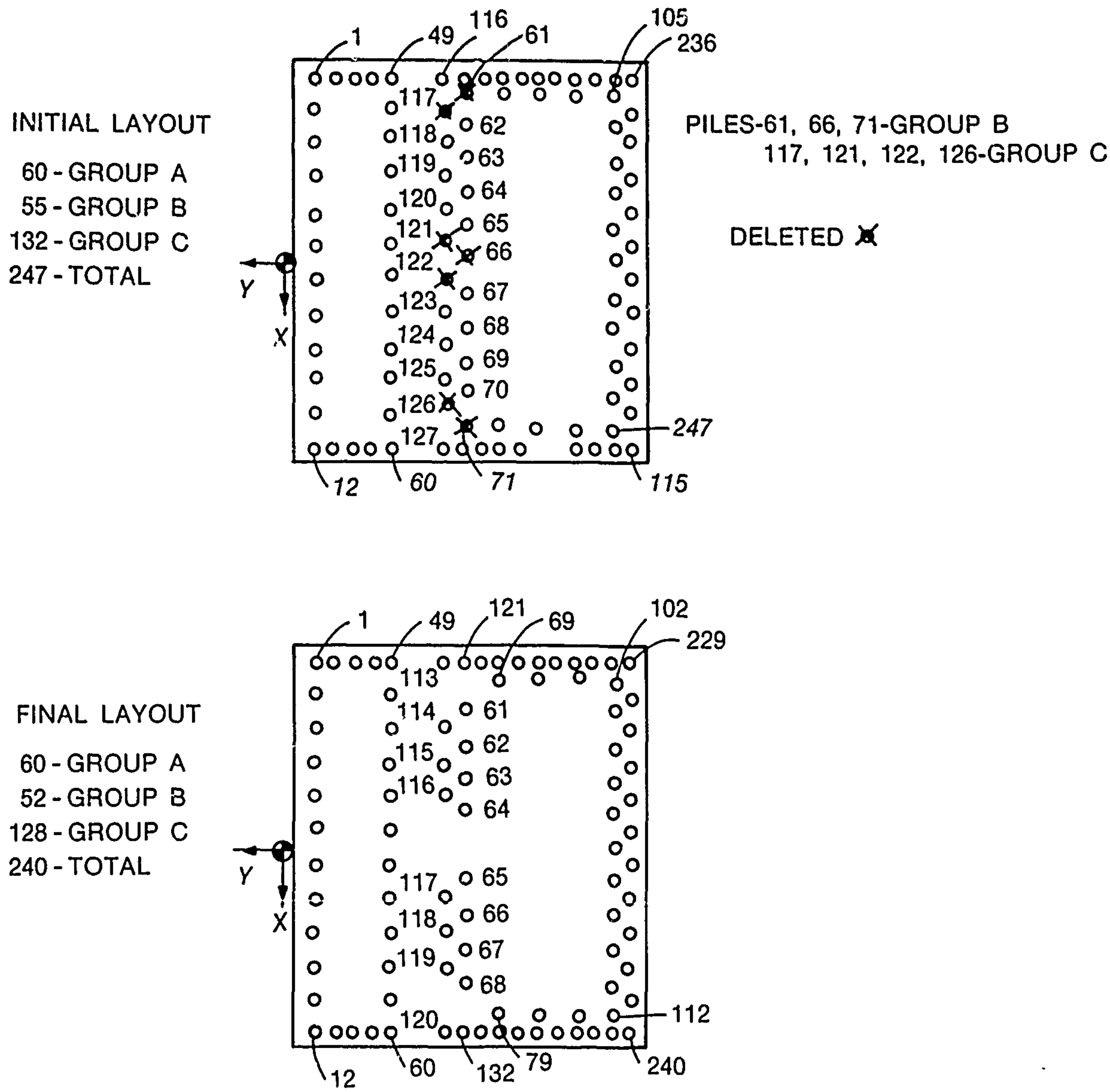


Figure B12. Initial and final pile layout for Example Problem 3

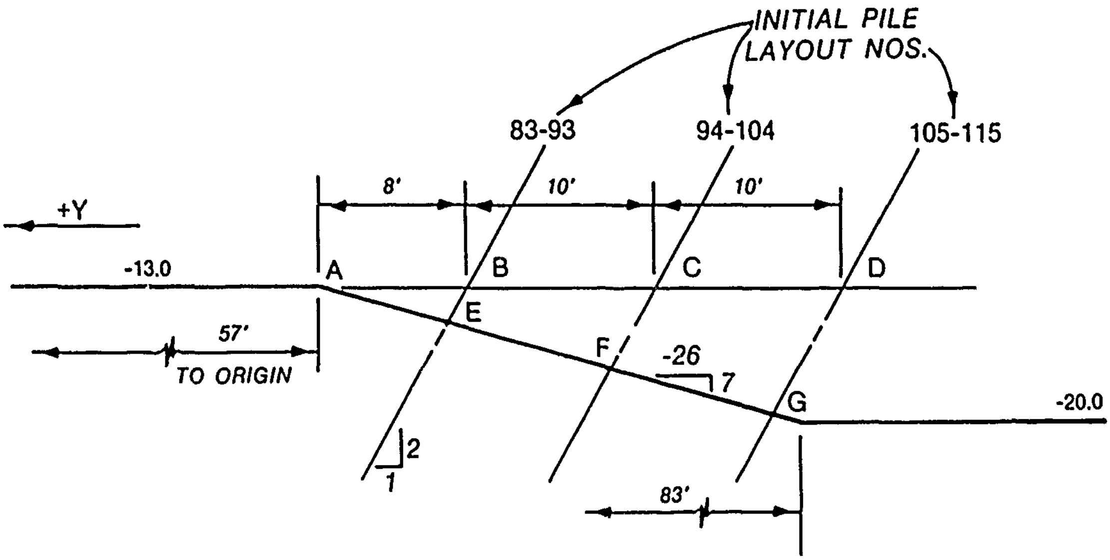


Figure B13. Sloped base, Group B

NOTES: Generate rows 83-93, 94-104, and 105-115 as follows:

1. Enter coordinates of Pile 61 (1st pile in Group B)

   PILE 61 -45.0 -45.0 0

2. Generate Y coordinate of rows 83, 94, and 105 at their intersection with -13.0 elevation (Pts B, C, D)

   ROW X 11 61 10 AT 9.0

   REPEAT 5 4 AT -10.0

3. Generate true coordinates of rows 83, 94, & 105 at their intersection with sloped base (Pts E, F, G)

   SLP = $\frac{-26}{7}$

   AZ

   SLOPE YZ -3.714 -57.0 0.0 83 to 115

   Plane AXY List of piles

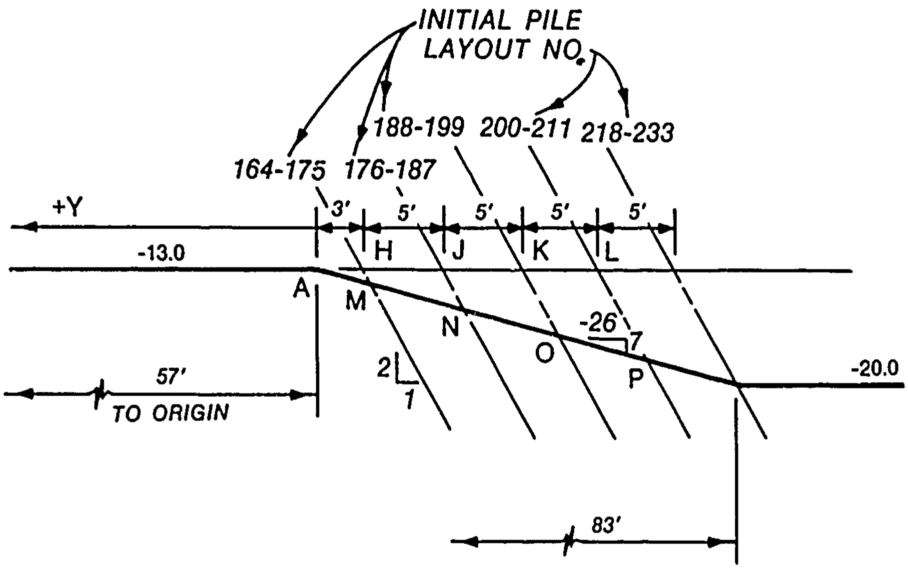


Figure B14. Sloped base, Group C

NOTES: Generate rows 164, 176, 188, 200 as follows:

1. Enter coordinates of Pile 116 (1st pile in Group C)

   PILE 116 -49.5 -40.0 0

2. Generate Y coordinate of rows 164, 176, 188, 200 at their intersection with -13.0 elevation (Pts H, J, K, L)

   ROW X 12 116 11 AT 9.0

   REPEAT 8 7 AT -5.0

3. Generate true coordinates of rows 164, 176, 188, 200 at their intersection with sloped base (Pts M, N, O, P)

$$\text{SLP} = \frac{-26}{7}$$

```
                   SLP        AXY     AZ
SLOPE    YZ     -3.714     -57.0     0.0     164 to 211
       Plane                                 List of piles
```

Both Groups B and C pile coordinates may be corrected for sloped base effects in one data line as follows:

SLOPE YZ -3.714 -57.0 0.0 83 TO 115 164 TO 211

Data Group	Line No.								
(a)		TITLE							
	10	EXAMPLE PROBLEM 3							
	20	OLD RIVER LOW SILL CONTROL STRUCTURE							
(b)		PILE PROPERTIES							
			E	I1	I2	A	C33	B66	LIST
	30	PROP	29000	261	729	21.4	1.0	0	ALL
(c)		SOIL DESCRIPTION							
			PSOIL	ESOIL	LENGTH	L	LU	LIST	
	40	SOIL	NH	0.019	L	90	0	ALL	
(d)		FIXITY							
		FIXITY	LIST						
	50	PIN	ALL						
(e)		PILE STIFFNESS - Omit (Based on Soil and Pile Properties)							
(f)		TENSION PILE STIFFNESS MODIFIER - Omit (Not Desired)							
(g)		ALLOWABLE LOADS STEEL AND TIMBER PILES							
			SHAPE	AC	AT	ACC	ATT	AM1	AM2	LIST
	60	ALLOW	H	200	80	363.8	385.2	644.4	1926	ALL
(h)		DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE OR REINFORCED CONCRETE PILES - Omit (Not Applicable)							
(i)		ALLOWABLE STRESS CHECK - PRESTRESSED CONCRETE PILES - Omit (Not Applicable)							
(j)		UNSUPPORTED PILE DATA - Omit (Not Applicable)							
(k)		DESIGN MOMENT FACTORS FOR PINNED PILE							
			KMP1	KMP2	LIST				
	70	PMAXMOM	40.5	49.8	ALL				
(l)		MOMENT FACTORS FOR FIXED UNSUPPORTED PILES - Omit (Not Applicable)							
(m)		OVERSTRESS FACTORS - Omit (Default to 1.0)							

(n) PILE BATTER

```
                 BAT   LIST
80   BATTER      2.0   61 TO 247 (Vertical Piles 1 to 60 Default to 0)
```

(o) ANGLE TO BATTER DIRECTION

```
                 ANG   LIST
90   ANGLE       90    1 to 115
100  ANGLE       270   116 to 247
```

(p) PILE COORDINATES

```
                 PN1   X1      Y1      Z1   PN2   X2      Y2      Z2
110  PILE        1     -49.5   -6.0    0    61    -45.0   -45.0   0
120  PILE        116   -49.5   -40.0   0    212   -49.5   -83.5   7.0
```

(q) PILE ROW GENERATION

```
                 AXIS   NP   PN1   SP1... SP2...
130  ROW         X      12   1     11 AT 9.0
```

(r) REPEAT ROWS OF PILES

```
                 NR   SP1... SP2...
140  REPEAT      5    4 AT -5.0
```

DATA LINES 130 AND 140 GENERATE COORDINATES OF PILES 1 THROUGH 60. DATA LINES 150 AND 160 GENERATE COORDINATES OF PILES 61 THROUGH 115. DATA LINES 170 THROUGH 200 GENERATE 116 THROUGH 247.

(s) PILE ARC GENERATION - Omit (Not Applicable)

(t) REPEAT ARCS OF PILES - Omit (Not Applicable)

(u) DUPLICATE PILE ZONES - Omit (Not Applicable)

(v) ROTATE PILE ZONES - Omit (Not Applicable)

(w) SLOPED BASE DESCRIPTION

```
                 PLANE   SLP      AXY     AZ   LIST
210  SLOPE       YZ      -3.714   -57.0   0    83 to 115   164 to 211
```

(x) PILE DELETION

```
                 RENUM   IPRI   LIST
220  DELETE      REN     Y      61   66   71   117  121   122   126
```

(y) LOAD CASES

```
                 LCN   PX   PY      PZ      MX         MY   MZ
300  LOAD        1     0    12000   20000   -1000000   0    0
```

(z) SPECIFIED PILE CAP DISPLACEMENTS - Omit (Not Desired)

(aa) OUTPUT AT TERMINAL

```
                 LIST
400  TOUT        1   2   4   5
```

(cc) PILE STIFFNESS OUTPUT

LIST

410 PSO (Default to Pile #1)

(dd) PILE CAP DISPLACEMENT - Omit (Default to Origin)

(ee) PILE FORCE OUTPUT

LIST

420 PFO 1 60 62 72 83 115 116 163 211 212 247

(Numbering of Piles Follows Sequence Before Renumbering)

(ff) PILE COORDINATES OUTPUT

LIST

430 PLB 1 60 62 72 83 115 116 163 211 212 247

(Numbering of Piles Follows Sequence Before Renumbering)

(gg) PLOT FILE OPTION - Omit (Graphics not displayed)

<u>Listing of Data File for Problem 3</u>

```
10 EXAMPLE PROBLEM 3-
20 OLD RIVER LOW SILL CONTROL STRUCTURE
30 PROP 29000 261 729 21.4 1.0 0 ALL
40 SOIL NH 0.019 L 90 0 ALL
50 PIN ALL
60 ALLOW H 200 80 363.8 385.2 644.4 1926 ALL
70 PMAXMOM 49.5 49.8 ALL
80 BATTER 2.0 61 TO 247
90 ANGLE 90 1 TO 115
100 ANGLE 270 116 TO 247
110 PILE 1 -49.5 -6.0 0 61 -45.0 -45.0 0
120 PILE 116 -49.5 -40.0 0 212 -49.5 -83.5 7.0
130 ROW X 12 1 11 AT 9.0
140 REPEAT 5 4 AT -5.0
150 ROW X 11 61 10 AT 9.0
160 REPEAT 5 4 AT -10.0
170 ROW X 12 116 11 AT 9.0
180 REPEAT 8 7 AT -5.0
190 ROW X 12 212 11 AT 9.0
200 REPEAT 3 2 AT -5.0
210 SLOPE YZ -3.714 -57.0 0.0 83 TO 115 164 TO 211
220 DELETE REN Y 61 66 71 117 121 122 126
300 LOAD 1 0 -12000 20000 -1000000 0 0
400 TOUT 1 2 4 5
410 PSO
420 PFO 1 60 62 72 83 115 116 163 164 211 212 247
430 PLB 1 60 62 72 83 115 116 163 164 211 212 247
```

Execution of Problem 3

```
********************************
*  CORPS PROGRAM *  X0080      *
*    CDC VERSION * 86/09/02-A  *
********************************

CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE  88/04/07   RUN TIME  14.43.25


     FOR PILES WITH UNSUPPORTED HEIGHT:
          A. CPGA CANNOT CALCULATE PMAXIMOM FOR NH TYPE SOIL
          B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
             NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
             WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

     ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


 DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
 ENTER F OR I.
? F
 ENTER DATA FILE NAME.
? X80D3
 EXAMPLE PROBLEM 3
 OLD RIVER LOW SILL CONTROL STRUCTURE

 WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
? N


 RESEQUENCING . . .
```

PILE NUMBERS

NEW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
OLD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
NEW	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
OLD	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
NEW	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
OLD	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
NEW	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
OLD	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
NEW	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
OLD	62	63	64	65	67	68	69	70	72	73	74	75	76	77	78

NEW	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
OLD	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93
NEW	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
OLD	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108
NEW	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
OLD	109	110	111	112	113	114	115	116	118	119	120	123	124	125	127
NEW	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135
OLD	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142
NEW	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150
OLD	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157
NEW	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165
OLD	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172
NEW	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
OLD	173	174	175	176	177	178	179	180	181	182	193	184	185	186	187
NEW	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195
OLD	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202
NEW	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210
OLD	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217
NEW	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225
OLD	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232
NEW	226	227	228	229	230	231	232	233	234	235	236	237	238	239	243
OLD	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247

THERE ARE 240 PILES AND
1 LOAD CASES IN THIS RUN.

ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX

	X	Y	Z
WITH DIAGONAL COORDINATES = (	-49.50 ,	-93.50 ,	.00)
(	49.50 ,	-6.00 ,	7.00)

****

PILE PROPERTIES AS INPUT

E	I1	I2	A	C33	B66
KSI	IN**4	IN**4	IN**2		
.29000E+05	.26100E+03	.72900E+03	.21400E+02	.10000E+01	.00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

ALL

****

SOIL DESCRIPTIONS AS INPUT

NH	ESOIL	LENGTH	L	LU
	K/IN**3		FT	FT
	.19000E-01	L	.90000E+02	.00000E+00

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

ALL

****

PILE STIFFNESSES AS CALCULATED FROM PROPERTIES

.32445E+02	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	.23513E+02	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	.00000E+00	.57463E+03	.00000E+00	.00000E+00	.00000E+00
.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00

THIS MATRIX APPLIES TO THE FOLLOWING PILES -

1

****

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X FT	Y FT	Z FT	BATTER	ANGLE	LENGTH FT	FIXITY
1	-49.50	-6.00	.00	V	90.00	90.00	P
60	49.50	-26.00	.00	V	90.00	90.00	P
61	-36.00	-45.00	.00	2.00	90.00	90.00	P
69	-45.00	-55.00	.00	2.00	90.00	90.00	P
80	-45.00	-64.05	1.90	2.00	90.00	90.00	P
112	45.00	-81.68	6.64	2.00	90.00	90.00	P
113	-49.50	-40.00	.00	2.00	270.00	90.00	P
156	49.50	-55.00	.00	2.00	270.00	90.00	P
157	-49.50	-60.47	.93	2.00	270.00	90.00	P
204	49.50	-77.80	5.60	2.00	270.00	90.00	P
205	-49.50	-83.50	7.00	2.00	270.00	90.00	P
240	49.50	-93.50	7.00	2.00	270.00	90.00	P

						21600.00	

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	.0	-12000.0	20000.0	-1300000.0	.0	.0

240 PILES 1 LOAD CASES

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 52.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	.8195E-08	-.3800E+00	.1851E+00	.1119E-03	-.2862E-12	.1859E-11

```
******************************************************************************
```

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF
1	-12.3	.0	101.7	.0	614.0	.0	.51	.60
60	-12.3	.0	86.3	.0	614.0	.0	.43	.56
61	-12.8	.0	-33.6	.0	639.2	.0	.42	.42
69	-12.6	.0	-40.5	.0	629.5	.0	.51	.43
80	-12.5	.0	-47.4	.0	624.4	.0	.59	.45
112	-12.4	.0	-61.2	.0	616.5	.0	.77	.48
113	9.1	.0	165.2	.0	-454.3	.0	.83	.69
156	9.4	.0	154.8	.0	-468.8	.0	.77	.67
157	9.6	.0	151.4	.0	-476.0	.0	.76	.66
204	10.1	.0	141.0	.0	-501.8	.0	.70	.65
205	10.2	.0	137.5	.0	-510.1	.0	.69	.64
240	10.4	.0	130.6	.0	-519.8	.0	.65	.63

SHOULD THE INPUT FILE NAMED 'X80D3 ' BE LISTED? (Y OR N)
? N

ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
RUN CPGA AGAIN? (Y OR N)
? N

NO FILES WERE GENERATED DURING THIS RUN.
EXIT.
/

Output for Example Problem 3

15. Selection of piles for output display was based on the pile location.

Group A Piles
Loads should vary linearly by rows between Piles 1 and 60

Group B Piles
Loads should vary linearly by rows between Piles 61 and 69, also between 80 and 112 (within sloped base section)

Group C Piles
Loads should vary linearly by rows between Piles 113 and 156, between 157 and 204 (within sloped base section), and between 205 and 240.

Hence, Piles 1, 60, 61, 69, 80, 112, 113, 156, 157, 204, 205, and 240 were selected for output display.

NOTE: Pile numbers described in input are based on sequence before renumbering. Pile numbers in output display are based on sequence after renumbering.

Check CPGA output

Pile No. 80

Part I, User's Manual,

Equation 2

$$ALF = \left(\frac{-F3}{AT}\right)\left(\frac{1}{OSFT}\right) = \left[\frac{-(-47.4)}{80}\right]\left(\frac{1}{1.0}\right) = 0.5925$$

0.59 from output ok

Equation 4

$$CBF = \left(\frac{-F3}{ATT} + MF1\,\frac{|M1|}{AM1} + MF2\,\frac{|M2|}{AM2}\right)\frac{1}{OSFT}$$

$$= \left[\frac{-(-47.4)}{385.2} + 1.0\,\frac{0}{644.2} + 1.0\,\frac{624.4}{1926}\right]\frac{1}{1.0}$$

$$= 0.123 + 0.324 = 0.447$$

0.45 from output ok

Example Problem 4, Cantilever Pile Group

16. The problem represents a cantilever pile foundation used to support a bridge pier. The problem is illustrated on Figure B15. The piles are 16- by 16-in. prestressed concrete, battered at 1 on 4 with the following properties:

$$E = 4{,}000{,}000 \text{ psi}$$

$$A = 256 \text{ in.}^2$$

$$I = 5{,}461 \text{ in.}^4$$

17. The piles were assumed to be 135 ft long with no load transferred down the pile by friction. The soil has a constant of horizontal subgrade reaction of 10 pci.

18. The same problem was also run using steel H-Piles (HP 14 X 73). This is shown on pages 28 through 30.

Hand Computations Verify Results

19. The results of the combined bending and axial load checks were verified by hand computations for the prestressed concrete piles and the steel H-Piles. The results of the allowable stress checks for prestressed concrete piles were verified by hand computations as well.

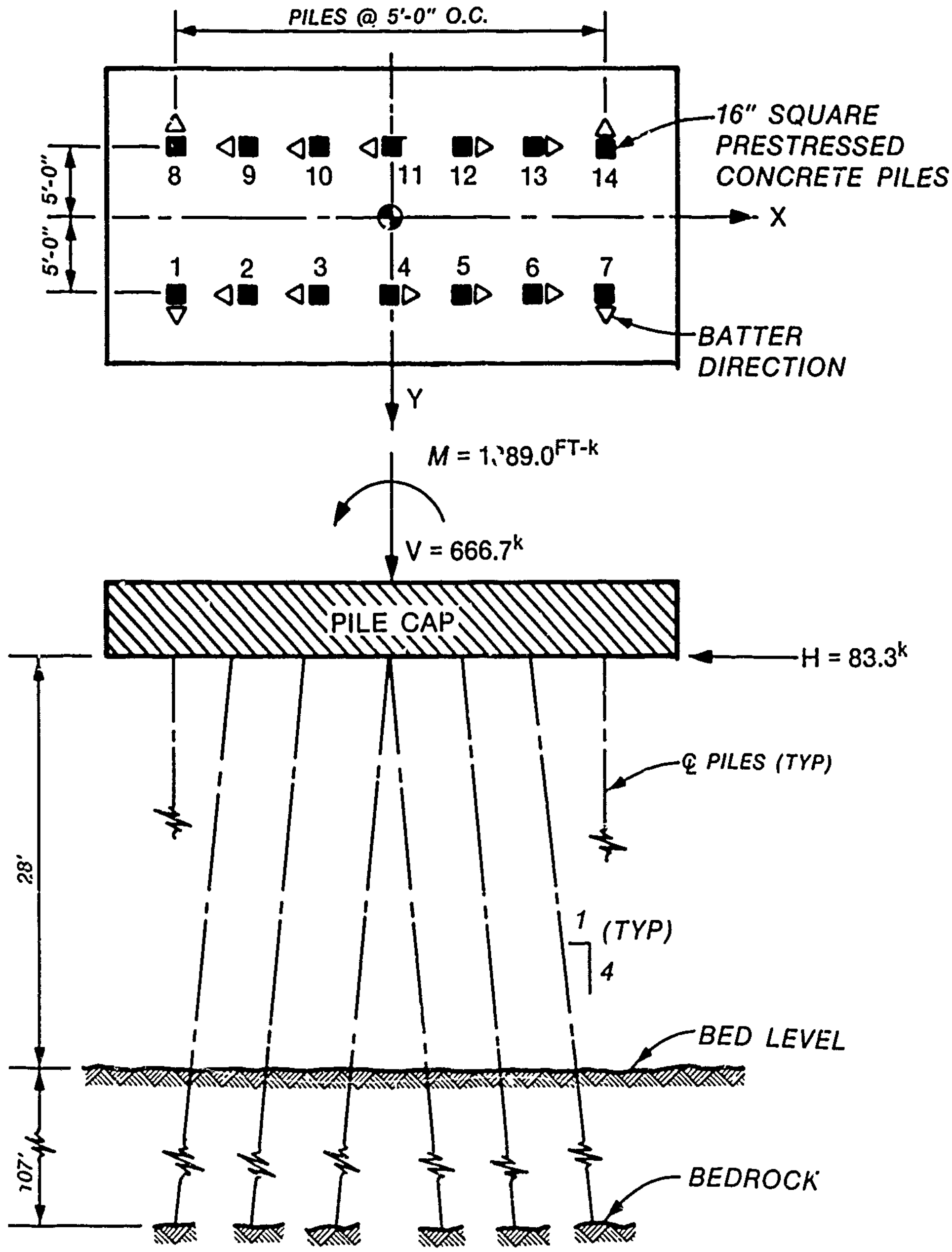
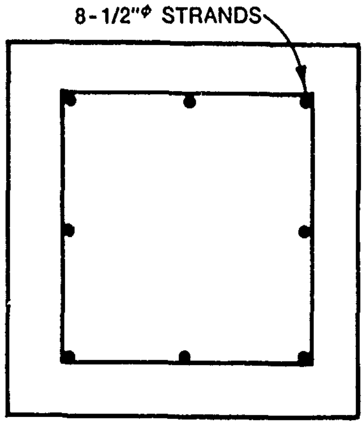


Figure B15. Pile group layout for Problem 4



16- × 16-in. Pile

$Ag = 256\ in.^2$

$S = 683\ in.^3$

$f'_c = 5,000$ psi

$fpu = 270,000$ psi

$I = 5,461\ in.^4$

$E_{strands} = 28,000$ ksi, Area = 0.153 sq in.

Strands are stressed initially to 0.7 fpu

Total losses are assumed to be 22%

Initial prestress force = 0.7(8)0.153(270) = 231 kips

Final prestress force = 0.78(231) = 180 kips

FPC (final prestress) = 180/256 = $\boxed{0.700\ \text{ksi}}$

IPC (initial prestress) = 231/256 = $\boxed{0.900\ \text{ksi}}$

FA (allowable concrete stress) = $0.45f'_c$ = $\boxed{2.25\ \text{ksi}}$

<u>Strain in strands @ final prestress</u>

$\varepsilon_f = S/E = [180/8(0.153)](1/28,000) = 0.0053$ in./in.

$PO = 0.85f'_cAg - \varepsilon_s EsAs$

$$= 0.85(5)256 - (0.0053 - 0.0030^{*})28,000(8)0.153 = \boxed{1,010\ \text{kips}}$$

where (0.0053 - 0.0030) is the strain in strands at ultimate, or final prestress strain - concrete ultimate strain

PT = 8(0.153)225 = $\boxed{275\ \text{kips}}$

where 225 ksi is stress in strands @ yield, see Figure B16.

* Refer to paragraph 10.2.3 ACI 318-83

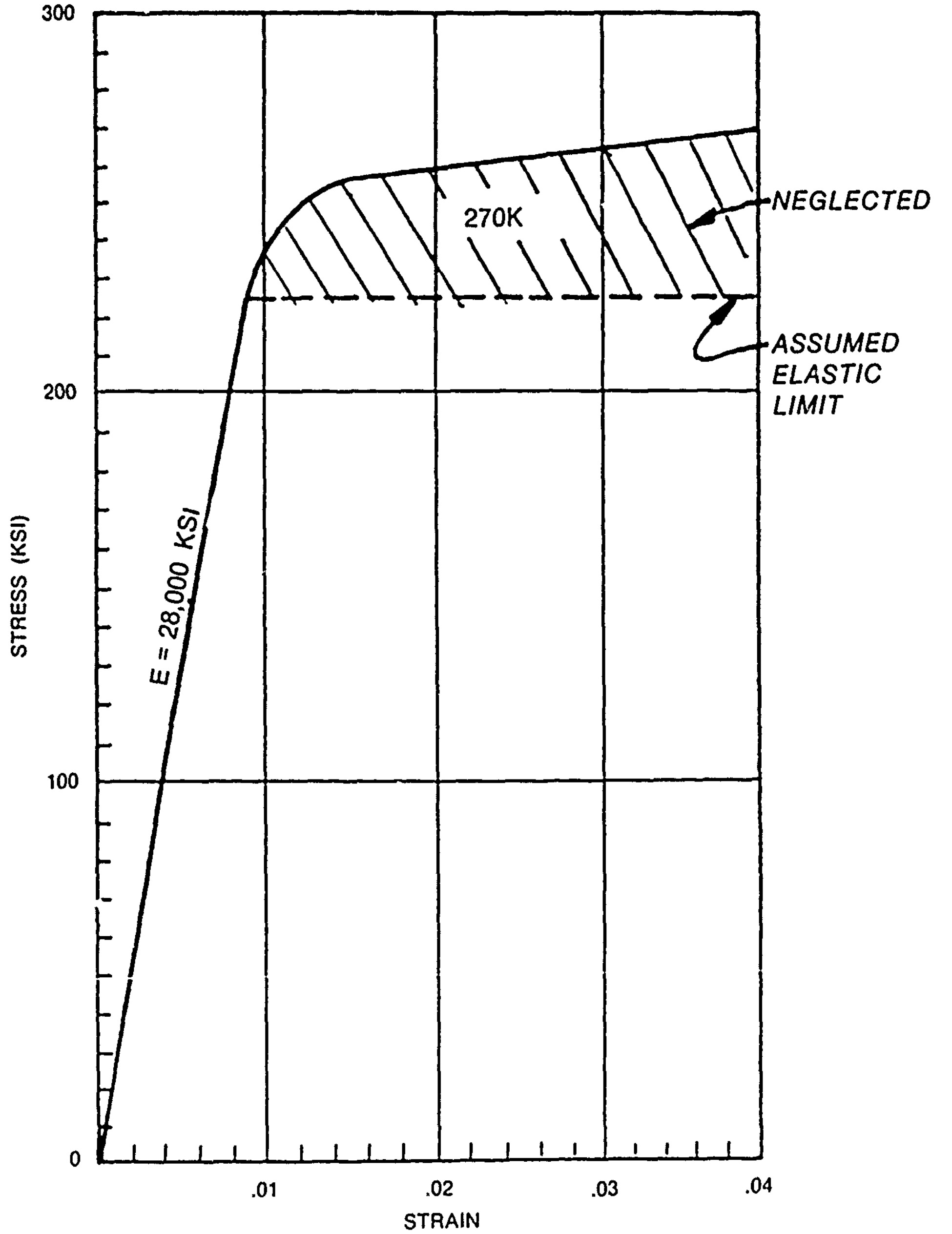
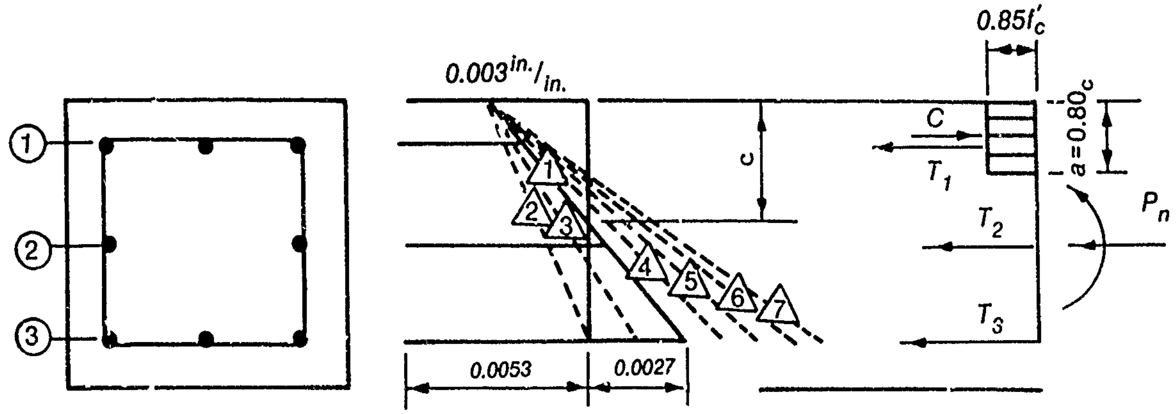


Figure B16. Stress-strain relation for 270-k stress-relieved strand



△	c (in)	ε_1	ε_2	ε_3	T_1	T_2	T_3	C	Pn	Mn
1	7.10	0.0034	0.0058	0.0080	43.7	49.7	102.8	386.2	189.8^k	2,317.8$^{\prime\prime k}$
2	13.50	0.0028	0.0041	0.0053	36.0	35.1	68.1	734.4	595.2	2,086.0
3	9.42	0.0031	0.0049	0.0066	39.8	42.0	84.8	512.4	345.8	2,416.0
4	6.04	0.0036	0.0064	0.0090	46.3	54.8	102.8	328.6	124.7	2,145.7
5	5.26	0.0038	0.0070	0.0100	48.8	60.0	102.8	286.1	74.5	1,983.8
6	4.66	0.0039	0.0077	0.0110	50.1	66.0	102.8	253.5	34.6	1,845.3
7	4.18	0.0040	0.0081	0.0120	51.4	68.5	102.8	227.1	4.4	1,719.8

Sample computations for Point △1 on interaction curve, taken from tabulation on previous page.

$$\frac{c}{0.0030} = \frac{(16 - 2.5)}{0.0030 + 0.0027}, \quad c = 7.10 \text{ in.}$$

$$\varepsilon_1 = 0.0053 - \frac{(7.10 - 2.5)}{7.10}(0.0030) = 0.0034 \text{ in./in.}$$

$$\varepsilon_2 = 0.0053 + \frac{(8.00 - 7.10)}{13.50 - 7.10}(0.0027) = 0.0057$$

$$\varepsilon_3 = 0.0053 + 0.0027 = 0.0080 \qquad \varepsilon \text{ @ yield}$$

$$T_1 = 0.0034(28{,}000)(0.153)3 = 43.7^k$$

$$T_2 = 0.0057(28{,}000)(0.153)2 = 48.8^k$$

$$T_3 = 0.0080(28{,}000)(0.153)3 = 102.8^k$$

$$C = 0.80(7.10)0.85(5)16 = 386.2^k$$

$$Pn = C - (T_1 + T_2 + T_3) = 386.2 - (43.7 + 48.8 + 102.8) = 190.9^k$$

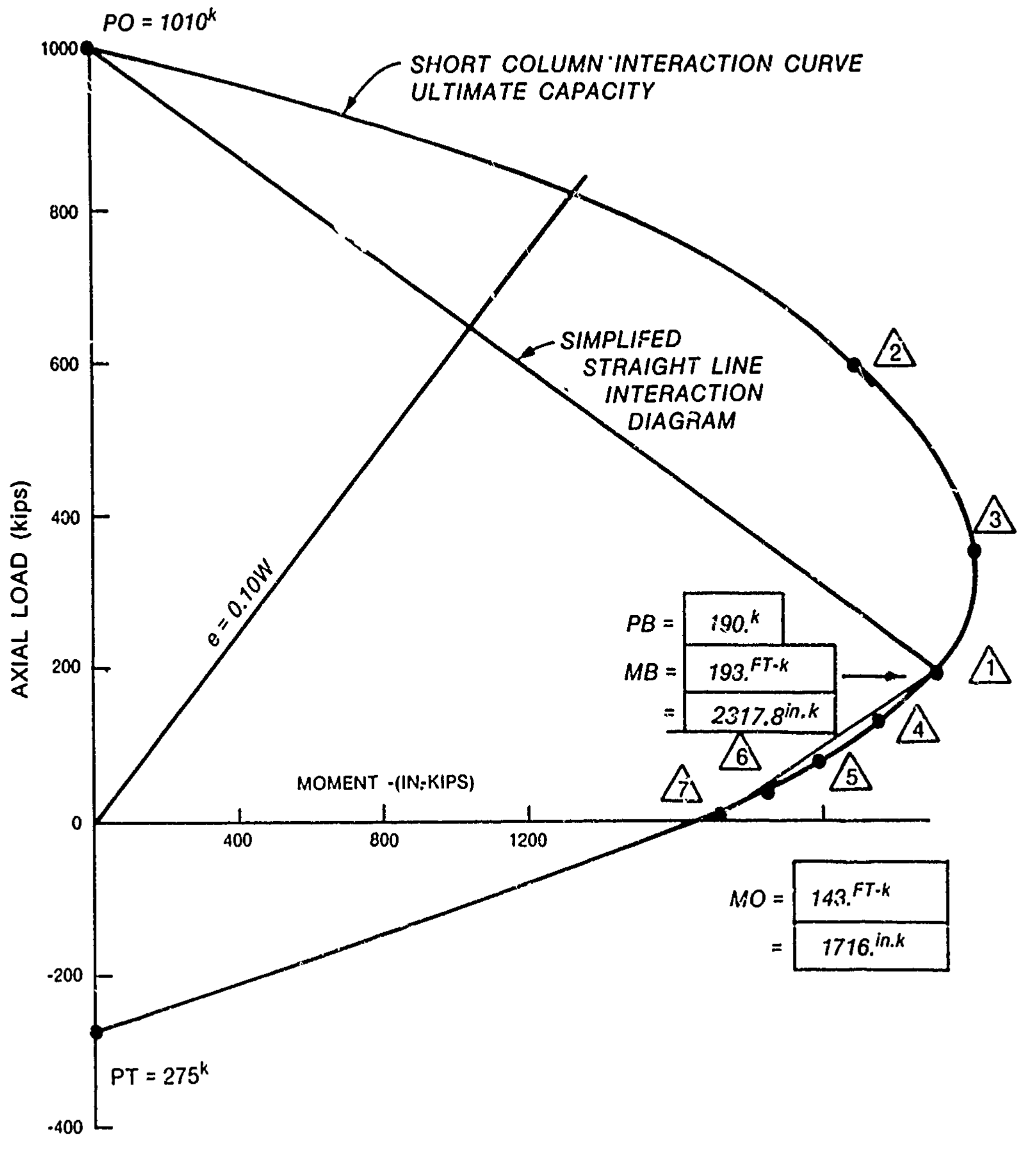
$$\text{Use } \quad Pn = 190^k$$

$$Mn = C(8 - 0.80c/2) - T_1(8 - 2.5) + T_3(8 - 2.5)$$

$$= 386.2(5.16) - 43.7(5.5) + 102.8(5.5) = 2{,}317.8 \text{ in.-kip}$$

Point △1 represents the actual balance point concrete at yield ($\varepsilon_c = 0.0030$), steel at yield ($\varepsilon_s = 0.0080$)

Other points (△2 - △7) are established by arbitrarily picking a location of the N/A, computing the corresponding strains and forces in the strands and concrete; then determining the external forces (axial load and moment) required to produce equilibrium.


PO = 1010^k
SHORT COLUMN INTERACTION CURVE
ULTIMATE CAPACITY
SIMPLIFED
STRAIGHT LINE
INTERACTION
DIAGRAM
e = 0.10W
AXIAL LOAD (kips)
1000
800
600
400
200
0
-200
-400
MOMENT -(IN-KIPS)
400
800
1200
PB = 190.^k
MB = 193.^FT-k
= 2317.8^in.k
MO = 143.^FT-k
= 1716.^in.k
PT = 275^k
1
2
3
4
5
6
7

Allowable axial forces based on soil properties or code requirements

for this problem:

$$AC = 0.2f'_cAg = 0.2(5)256 = \boxed{256 \text{ kips}}$$

$$AT = \frac{AC}{2} = \boxed{128 \text{ kips}}$$

<u>Uncracked section properties</u>

$$I_g = \frac{1}{12}bd^3 = \frac{1}{12}(16)(16)^3 = 5,461 \text{ in.}^4$$

$$E_c = 33w\sqrt{wf'_c} = 33(145)\sqrt{145(5,000)}$$

$$E_c = 4,000,000 \text{ psi} = 4,000 \text{ ksi}$$

$$E_cI_g = 4,000(5,461) = 21,844,000$$

<u>Cracked section properties</u>

$$E_cI_{cr} = \frac{(E_cI_g/2.5)}{1 + Bd}$$

$$Bd = \frac{\text{Dead load moment}}{\text{Total moment}} = \frac{1}{2} = 0.5$$

$$E_cI_{cr} = \frac{4,000(5,461)/2.5}{1 + 0.5} = 5,825,000$$

Use cracked section properties when determining the critical buckling load (PCR) otherwise, use uncracked section properties.

Critical buckling load computations (Method 1)

(Method 1 as described in "Lateral Load Capacity of Piles," M. T. Davisson, Highway Research Record #333.)

Unsupported length (L_T) = $L_u + L_f$

L_u = free standing length = 28.0'

L_f = depth to fixity = 1.8T

$$T = \sqrt[5]{\frac{EI}{n_h}}\text{, granular soil, } n_h = 10 \text{ pci}$$

$$T = \sqrt[5]{\frac{5{,}825{,}000}{0.010}} = 56.63'' = 4.72'$$

$$L_f = 1.8T = 8.50'$$

$$L_T = 28.0 + 8.50 = 36.50'$$

$$Pcr = \frac{\pi^2 EI}{(KL_T)^2}$$

Assume K = 1.0 nontranslating, pinned @ cap

There will be some translation but assume it is small for now and check later.

$$Pcr = \frac{\pi^2(5{,}825{,}000)}{[36.50(12)]^2} = 300 \text{ kips}$$

$$\frac{KL_T}{r} = \frac{36.50(12)}{0.3(16)} = 92 < 100$$

$\frac{KL_T}{r}$ = 100 is the maximum limit for the use of the moment magnifier method

Critical buckling load computations (Method 2)

(Method 2 as described in "Buckling Strength of Pile," Nai C. Yang, Highway Research Record #147.)

$T = 56.63'' = 4.72'$

Free standing length factor (m) = L_u/T

$$m = \frac{28(12)}{56.63} = 5.93$$

From Figure B17 for m = 5.93, (G) = 0.019

$$Pcr = \frac{\pi^2 EI}{T^2}(G) = \frac{\pi^2(5{,}825{,}000)(0.019)}{(56.63)^2} = 340 \text{ kips}$$

340 kips--slightly more than the 300 kips computed by method 1. The reduction in the critical buckling load should be checked due to translation.

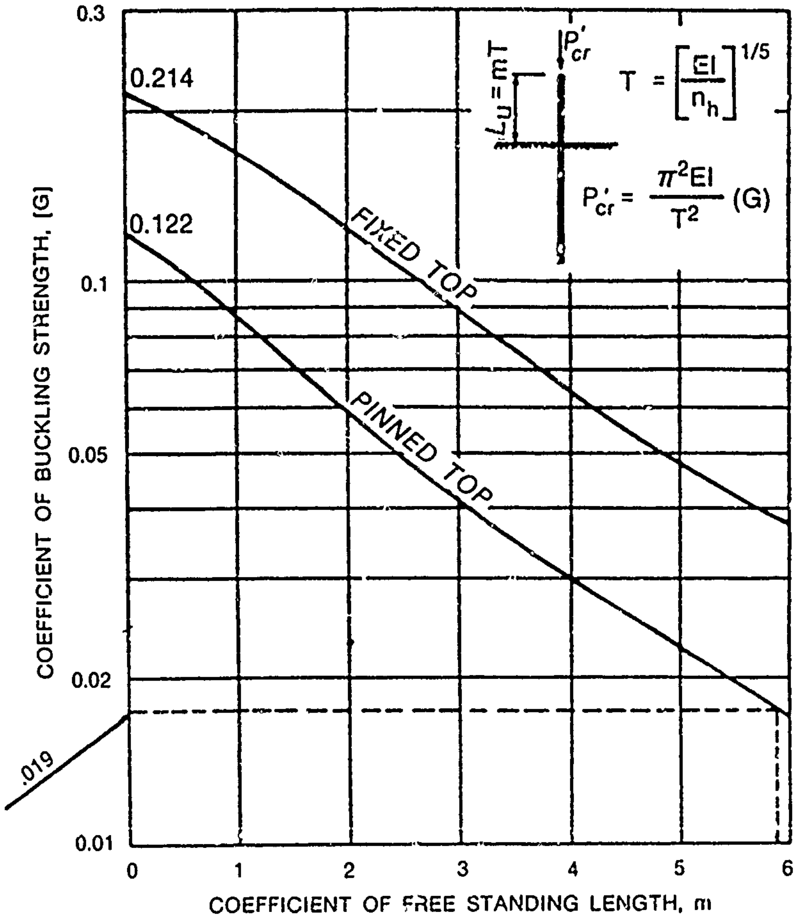


Figure B17. Coefficient of critical buckling strength

Critical Buckling Load as a function of the translation in inches - Method 2

$$P'_{cr} = Pcr\left(1 - G_T \frac{c}{r^2} Y\right)$$

P_{cr} = critical buckling load - no translation

P'_{cr} = critical buckling load with translation

G_T = coefficient of translation - Figure B18

c = distance from neutral axis to outer fiber = $\frac{16''}{2}$ = 8"

r = radius of gyration = 0.3t = 0.3(16) = 4.8"

For m = 5.93, G_T = 0.21

$$P'_{cr} = P_{cr}\left[1 - 0.21 \frac{(8)}{(4.8)^2} Y\right] = Pcr(1 - 0.07Y)$$

where Y is the translation in inches

Y	(1 - 0.07Y)
0.5	0.97
1.0	0.93
2.0	0.86
3.0	0.79

Assume pile cap displacement is 1" or less

P'_{cr} = 0.93(340) = 316 kips

Use critical buckling load equal to $\boxed{316 \text{ kips}}$

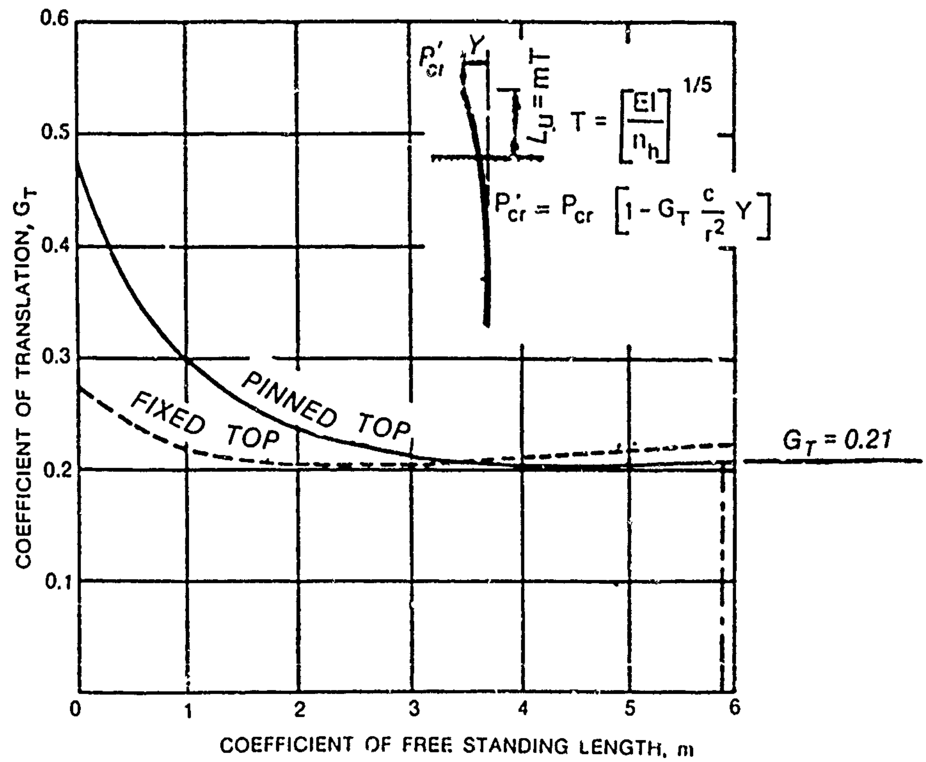


Figure B18. Coefficient of decrement of buckling strength

Compute Cm

$$Cm = 0.6 + 0.4\left(\frac{M1}{M2}\right)$$

Pinned top

$$Cm = 0.6 + 0.4\left(\frac{0}{M2}\right) = \boxed{0.6}$$

Minimum eccentricity

Spirally reinforced

EMIN = 0.10W = 0.10(16) = 1.6"

Compute design moment factors for pinned piles

Refer to Figure B19 "Buckling Strength of Pile," Nai C. Yang, Highway Research Record #147

For m = 5.93, (H) = 0.150

where

$$M = \frac{F(T)}{(H)} = (KMP) \times F$$

$$KMP1 = KMP2 = \frac{T}{(H)} = \frac{4.72}{0.150} = 31.50'$$

$$KMP2 = KMP2 = 31.50' = \boxed{378.0''}$$

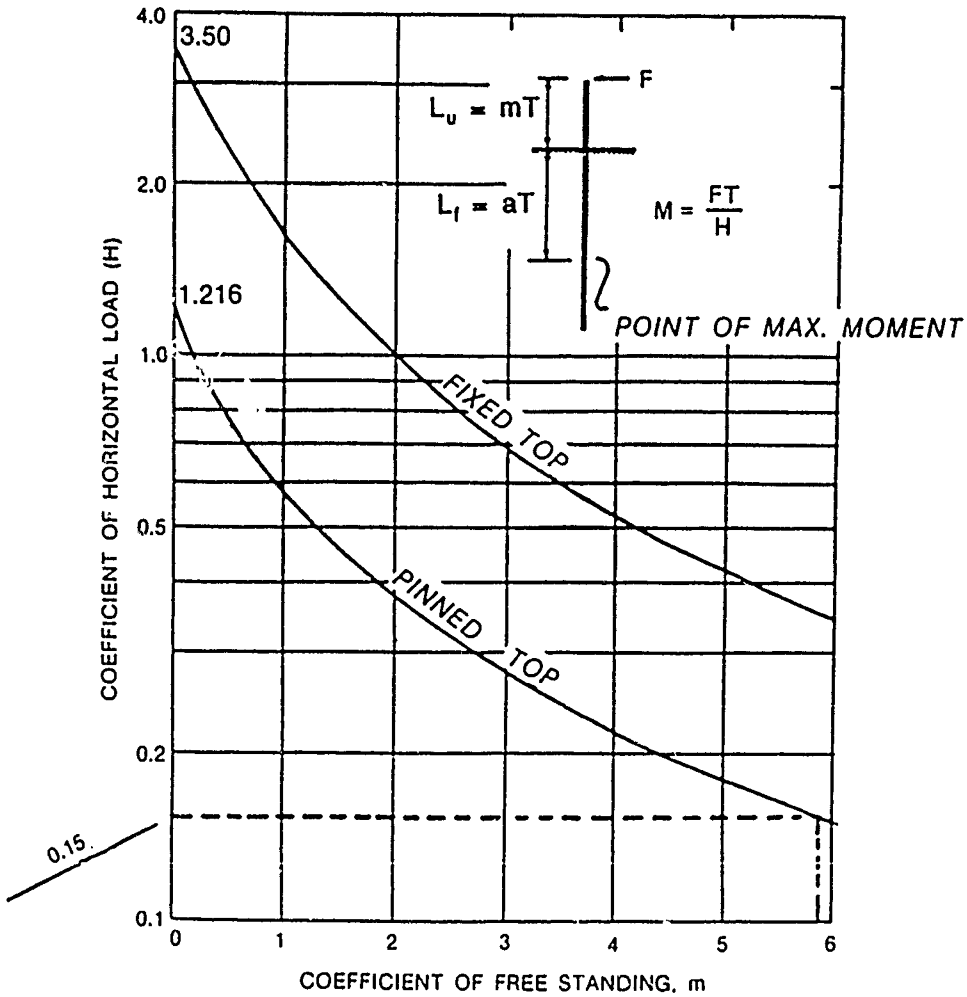


Figure B19. Coefficient of horizontal load capacity

Example Problem 4

INPUT TO CPGA

Data Group

(a) TITLE
CANTILEVER PILE GROUP

Data Group							
(b)	E	I1	I2	A	C33	B66	LIST
PROP	4000.	5461.	5461.	256.	1.0	0.	1 TO 14

Data Group						
(c)	PSOIL	ESOIL	LENGTH	L	LU	LIST
SOIL	NH	.010	L	135.	28.	1 TO 14

Data Group		
(d)	FIXITY	LIST
	PIN	1 TO 14

(e) PILE STIFFNESS
(Based on Soil and Pile Properties - Omit)

(f) TENSION PILE STIFFNESS MODIFIER
(Not used)

(g) ALLOWABLE LOADS STEEL and TIMBER PILES
(Not used)

(h) DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE PILES

DLS											
	SHAPE	AC	AT	PO	PT	PB	MB	MO	ST	W	LIST
	S	256.	128.	1010.	275.	190.	2316.	1716.	N	16	1 TO 14

(i) ALLOWABLE STRESS CHECK - PRESTRESSED CONC PILES

ASC								
	SHAPE	A	S	FPC	IPC	FA	FT	LIST
	S	256.	683.	0.700	0.900	2.250	0.000	1 TO 14

(j) UNSUPPORTED PILE DATA

UNSP							
	MATL	CM1	CM2	PCR1	PCR2	ST	LIST
	C	.6	.6	316.	316.	N	1 TO 14

(k) DESIGN MOMENT FACTORS (Pinned Piles)

PMAXMOM			
	KMP1	KMP2	LIST
	378.	378.	1 TO 14

Execution of Problem 4

```
********************************
* CORPS PROGRAM  * X0080    *
* MICRO VERSION  * 88/11/02  *
********************************


CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE: 89/08/10  RUN TIME: 10.09.16



   FOR PILES WITH UNSUPPORTED HEIGHT:
        A. CPGA CANNOT CALCULATE PMAXMOM FOR NH TYPE SOIL
        B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
           NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
           WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

   ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
ENTER F OR I.
F
ENTER DATA FILE NAME.
X80D4
CANTILEVER PILE GROUP
WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
N


THERE ARE  14 PILES AND
           1 LOAD CASES IN THIS RUN.

ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                               X          Y          Z
                             -----      -----      -----
WITH DIAGONAL COORDINATES = (   -15.00 ,   -5.00 ,     .00 )
                            (    15.00 ,    5.00 ,     .00 )


**********************************************************************

       PILE PROPERTIES AS INPUT


      E          I1          I2          A          C33         B66
     KSI        IN**4       IN**4       IN**2
  .40000E+04  .54610E+04  .54610E+04  .25600E+03  .10000E+01  .00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

   ALL
```

(l)	MOMENT FACTORS FOR UNSUPPORTED PILES (Fixed Only)						
	KMF1U	KMF2U	LIST				
	(Not Used Since Piles are Pinned)						
(m)	OVERSTRESS FACTORS						
	OSF	OSFT	LIST				
	(Not Used, Default to 1.0)						
(n)	PILE BATTER						
	BAT	LIST					
BATTER	4.	1 TO 14					
(o)	ANGLE TO BATTER DIRECTION						
	ANG	LIST					
ANGLE	0.	4 5 6 12 13					
ANGLE	90.	1 7					
ANGLE	180.	2 3 9 10 11					
ANGLE	270.	8 14					
(p)	PILE COORDINATES						
	PNn	Xn	Yn	Zn			
PILE	1	-15.	5.	0.			
	8	-15.	-5.	0.			
(q)	PILE ROW GENERATION						
	AXIS	NP	PN1	SP1			
ROW	X	7	1	6 AT 5.0			
ROW	X	7	8	6 AT 5.0			
(y)	LOAD CASES						
	LCN	PX	PY	PZ	MX	MY	MZ
	1	-83.3	0.	666.7	0.	1389.	0.
(aa)	OUTPUT						
TOUT	1 2 3 4 5 6 7						
(ee)	PILE FORCE OUTPUT						
	LIST						
PFO	1 TO 14						

##

SOIL DESCRIPTIONS AS INPUT

NH	ESOIL	LENGTH	L	LU
	K/IN**3		FT	FT
	.10000E-01	L	.13500E+03	.28000E+02

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

ALL

##

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X FT	Y FT	Z FT	BATTER	ANGLE	LENGTH FT	FIXITY
1	-15.00	5.00	.00	4.00	90.00	135.00	P
2	-10.00	5.00	.00	4.00	180.00	135.00	P
3	-5.00	5.00	.00	4.00	180.00	135.00	P
4	.00	5.00	.00	4.00	.00	135.00	P
5	5.00	5.00	.00	4.00	.00	135.00	P
6	10.00	5.00	.00	4.00	.00	135.00	P
7	15.00	5.00	.00	4.00	90.00	135.00	P
8	-15.00	-5.00	.00	4.00	270.00	135.00	P
9	-10.00	-5.00	.00	4.00	180.00	135.00	P
10	-5.00	-5.00	.00	4.00	180.00	135.00	P
11	.00	-5.00	.00	4.00	180.00	135.00	P
12	5.00	-5.00	.00	4.00	.00	135.00	P
13	10.00	-5.00	.00	4.00	.00	135.00	P
14	15.00	-5.00	.00	4.00	270.00	135.00	P

						1890.00	

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	-83.3	.0	666.7	.0	1389.0	.0

****

ORIGINAL PILE GROUP STIFFNESS MATRIX

.39333E+03	.32423E-05	.25939E-04	.17802E+05	-.99495E+05	-.11101E-02
.32423E-05	.17080E+03	-.64847E-04	.28286E+05	-.46690E-02	-.17169E-03
.25939E-04	-.64847E-04	.83302E+04	-.57126E-04	-.22850E-04	-.17802E+05
.17802E+05	.28286E+05	-.57126E-04	.32479E+08	-.15683E+05	-.10083E+00
-.99495E+05	-.46690E-02	-.22850E-04	-.15683E+05	.12263E+09	.48552E+00
-.11101E-02	-.17169E-03	-.17802E+05	-.10083E+00	.48552E+00	.69459E+07

14 PILES 1 LOAD CASES

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	-.2316E+00	-.2457E-01	.8048E-01	.1483E-03	-.5200E-04	.2063E-03

****

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1	F2	F3	M1	M2	M3	ALF	CBF	ASC	AST
	K	K	K	IN-K	IN-K	IN-K			KSI	KSI
1	-.2	.4	39.6	168.4	78.3	.0	.15	.34	1.42	.49
2	.4	.2	88.4	69.4	-141.9	.0	.35	.41	1.86	.74
3	.4	.2	90.3	61.9	-141.4	.0	.35	.42	1.88	.76
4	-.4	-.1	17.4	-34.0	167.2	.0	.07	.39	1.26	.47
5	-.4	-.1	19.3	-26.5	167.7	.0	.08	.38	1.26	.49
6	-.4	-.1	21.2	-19.0	168.2	.0	.08	.37	1.26	.51
7	-.1	.4	62.5	168.4	37.3	.0	.24	.28	1.50	.64
8	.2	-.4	47.6	-133.0	-57.3	.0	.19	.27	1.36	.61
9	.3	.2	73.7	69.4	-129.9	.0	.29	.26	1.61	.70
10	.3	.2	75.6	61.9	-129.5	.0	.30	.25	1.61	.72
11	.3	.1	77.5	54.4	-129.0	.0	.30	.26	1.62	.73
12	-.4	-.1	12.2	-26.5	150.5	.0	.05	.39	1.21	.49
13	-.4	-.1	14.1	-19.0	151.0	.0	.06	.38	1.20	.51
14	.0	-.4	47.7	-133.0	-10.9	.0	.19	.24	1.30	.68

****

PILE FORCES IN GLOBAL GEOMETRY

LOAD CASE - 1

PILE	PX K	PY K	PZ K	MX IN-K	MY IN-K	MZ IN-K
1	-.4	9.4	38.5	69.8	-145.2	36.3
2	-21.8	-.2	85.7	59.8	-126.1	15.0
3	-22.3	-.2	87.5	53.4	-125.7	13.3
4	3.8	-.1	17.0	29.3	-148.7	-7.3
5	4.3	-.1	18.8	22.9	-149.1	-5.7
6	4.7	-.1	20.7	16.4	-149.5	-4.1
7	-.4	15.1	60.6	33.2	-145.2	36.3
8	-.4	-11.7	46.2	51.0	-114.7	-28.7
9	-18.2	-.2	71.4	59.8	-115.5	15.0
10	-18.7	-.2	73.3	53.4	-115.1	13.3
11	-19.1	-.1	75.1	46.9	-114.7	11.7
12	2.6	-.1	11.9	22.9	-133.8	-5.7
13	3.0	-.1	13.8	16.4	-134.2	-4.1
14	-.4	-11.6	46.3	9.7	-114.7	-28.7

```
SHOULD THE INPUT FILE NAMED
X80D4
BE LISTED? (Y OR N)
Y
10 CANTILEVER PILE GROUP
20 PROP 4000. 5461. 5461. 256. 1.0 0.0 1 TO 14
30 SOIL NH .010 L 135. 28. 1 TO 14
40 PIN 1 TO 14
50 DLS S 256. 128. 1010. 275. 190. 2316. 1716. N 16 1 TO 14
60 ASC S 256. 683. 0.7 0.3 2.25 0.0 1 TO 14
70 UNSP C 0.6 0.6 316. 316. N 1 TO 14
80 PMAXMOM 378. 378. 1 TO 14
90 BATTER 4. 1 TO 14
100 ANGLE 0. 4 5 6 12 13
110 ANGLE 90. 1 7
120 ANGLE 180. 2 3 9 10 11
130 ANGLE 270. 8 14
140 PILE 1 -15. 5. 0.
150 8 -15. -5. 0.
160 ROW X 7 1 6 AT 5.0
170 ROW X 7 8 6 AT 5.0
180 LOAD 1 -83.3 0. 666.7 0. 1389. 0.
190 TOUT 1 2 3 4 5 6 7
200 PFO 1 TO 14


ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
*
RUN CPGA AGAIN? (Y OR N)
N


NO FILES WERE GENERATED DURING THIS RUN.
Stop - Program terminated.
```

Check CPGA output - Pile 1, OSF = 1.0

Equation 1:

$$ALF = \frac{F3}{AC} = \frac{39.6}{256} = 0.15 \qquad \text{ok}$$

Equations 7, 8, 9: $F3 = 39.6$

$$\frac{PB}{SF} = \frac{190}{2.5} = 76.0 > F3 \qquad \text{Use Equation 8}$$

$$MF1 = \frac{CM1}{1 - \left[\frac{F3(SF)}{PCR1}\right]} = \frac{0.6}{1 - \frac{39.6(2.5)}{(316)}} = 0.87 < 1.0 \qquad \text{use } 1.0$$

$$M1 = 168.4, \; M2 = 78.3$$

$$A = \tan^{-1} \left|\frac{M2}{M1}\right| = \tan^{-1} \frac{78.3}{168.4} = 24.94°$$

$$K = 1 - \left(\frac{24.94}{45}\right) 0.15 = 0.917$$

$$\sqrt{M1^2 + M2^2} = \sqrt{168.4^2 + 78.3^2} = 185.71 \text{"K}$$

Equation 8:

$$CBF = \frac{PB - SF(F3)}{PB + \frac{PB(MO)}{MB - MO}} + \frac{SF(MF1)(M1^2 + M2^2)^{1/2}}{K(MB)}$$

$$CBF = \frac{190 - 2.5(39.6)}{190 + \frac{190(1,716)}{2,316 - 1,716}} + \frac{2.5(1.0)(185.71)}{0.917(2,316)}$$

$$CBF = 0.12 + 0.22 = 0.34 \qquad \text{ok}$$

Part I, Equation 10:

$$* \ AST = \frac{F3}{A} - \frac{|M1|}{S} - \frac{|M2|}{S} + FPC$$

$$AST = \frac{39.6}{256} - \frac{168.4}{683} - \frac{78.3}{683} + 0.700$$

$$= 0.155 - 0.247 - 0.115 + 0.700 = 0.49 \qquad \text{ok}$$

Part I, Equation 11:

$$* \ ASC = \frac{F3}{A} + \frac{MF1(|M1|)}{S} + \frac{MF2(|M2|)}{S} + IPC$$

$$ASC = 0.155 + 1(0.247) + 1(0.115) + 0.900 = 1.42 \qquad \text{ok}$$

<u>Check CPGA output - Pile 3, OSF = 1.0</u>

Part I, Equation 1:

$$ALF = \frac{F3}{AC} = \frac{90.3}{256} = 0.35 \qquad \text{ok}$$

Equations 7, 8, and 9: $F3 = 90.3$

$$\frac{PB}{SF} = \frac{190}{2.5} = 76.0 < F3 \qquad \text{Use Equation 7}$$

$$MF1 = \frac{CM1}{1 - F3\left(\frac{SF}{PCR1}\right)} = \frac{0.6}{1 - \frac{90.3(2.5)}{316}} = 2.10$$

$$M1 = 61.9, \ M2 = -141.4$$

---

* The value of an allowable stress check (ASC) for unsupported prestressed concrete piles is questionable. The Design Load Strength (DLS) method, however, is based on ultimate strength design methods and moment magnification, and therefore, is considered a valid check for unsupported concrete piles.

$$A = \tan^{-1} \frac{|M1|}{|M2|} = \tan^{-1} \frac{61.9}{141.4} = 23.64°$$

$$K = 1 - \frac{23.64}{45.00} (0.15) = 0.921$$

$$\sqrt{M1^2 + M2^2} = \sqrt{61.9^2 + 141.4^2} = 154.35 \text{ in.-kips}$$

Part I, Equation 7:

$$CBF = \left[\frac{SF(F3) - PB}{PO - PB} + \frac{SF(MF1)(M1^2 + M2^2)^{1/2}}{K(MB)} \right]$$

$$CBF = \left[\frac{2.5(90.3) - 190}{1{,}010 - 190} + \frac{2.5(2.10)(154.35)}{0.921(2{,}316)} \right]$$

$$CBF = 0.04 + 0.38 = 0.42 \quad \text{ok}$$

Part I, Equation 10:

$$* \ AST = \frac{F3}{A} - \frac{|M1|}{S} - \frac{|M2|}{S} + FPC$$

$$AST = \frac{90.3}{256} - \frac{61.9}{683} - \frac{141.4}{683} + 0.700$$

$$= 0.353 - 0.091 - 0.207 + 0.700 = 0.76 \qquad \text{ok}$$

Part I, Equation 11:

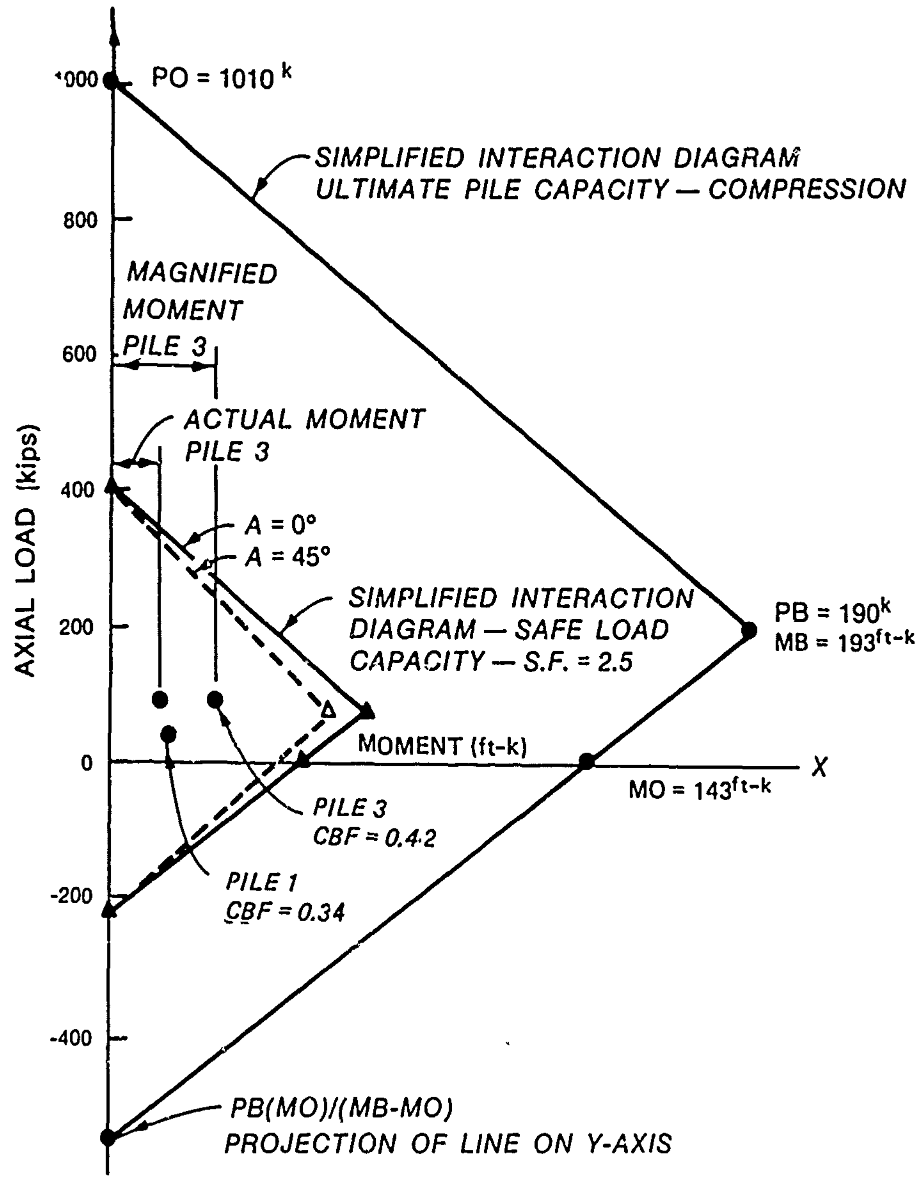
$$* \ ASC = \frac{F3}{A} + \frac{MF1(|M1|)}{S} + \frac{MF2(|M2|)}{S} + IPC$$

$$ASC = 0.353 + 2.10(0.091) + 2.10(0.207) + 0.900$$

$$= 0.353 + 0.191 + 0.435 + 0.900 = 1.88 \qquad \text{ok}$$

---

* See preceding page.


PO = 1010 k
SIMPLIFIED INTERACTION DIAGRAM
ULTIMATE PILE CAPACITY — COMPRESSION
MAGNIFIED
MOMENT
PILE 3
ACTUAL MOMENT
PILE 3
A = 0°
A = 45°
SIMPLIFIED INTERACTION
DIAGRAM — SAFE LOAD
CAPACITY — S.F. = 2.5
PB = 190k
MB = 193ft-k
MOMENT (ft-k)
X
MO = 143ft-k
PILE 3
CBF = 0.42
PILE 1
CBF = 0.34
PB(MO)/(MB-MO)
PROJECTION OF LINE ON Y-AXIS
AXIAL LOAD (kips)
1000
800
600
400
200
0
-200
-400

Run same problem using steel H-piles instead of prestressed concrete piles:

Use HP 14 × 73	
$A = 21.46$ in.^{3}	$I2 = 261.9$ in.^{4}
$I1 = 733.1$ in.^{4}	$S2 = 35.9$ in.^{3}
$S1 = 107.5$ in.^{3}	$r2 = 3.49$
$r1 = 5.85$	

<u>Critical buckling load for x and y axes</u>

Relative stiffness factor ~ T:

$$T = \left(\frac{EI}{n_n}\right)^{1/5}$$

$$T1 = \left[\frac{29{,}000(733.1)}{0.010}\right]^{1/5} = 73.36'' = 6.11'$$

$$T2 = \left[\frac{29{,}000(261.9)}{0.010}\right]^{1/5} = 59.72'' = 4.98'$$

Figure B17

$$P_{cr} = \frac{\pi^2 EI}{T^2}\ (G)$$

$$m = \frac{L_u}{T}$$

$$m1 = \frac{28}{6.11} = 4.6\ , \qquad m2 = \frac{28}{4.98} = 5.6'$$

$$G1 = 0.025 \qquad G2 = 0.019$$

$$P_{cr_1} = \frac{\pi^2(29{,}000)733.1(0.025)}{(73.36)^2} = 974 \text{ kips}$$

$$P_{cr_2} = \frac{\pi^2(29{,}000)262.9(0.019)}{(59.72)^2} = 399 \text{ kips}$$

Reduce critical buckling values assuming a 1-in. displacement as per PCC piles:

$$P'_{cr} = P_{cr}\left(1 - GT\frac{C}{r^2}Y\right)$$

$$= P_{cr}\left[1 - 0.21\frac{7}{(3.49)^2}(1)\right] = 0.88\ P_{cr}$$

$$P'_{cr_1} = 0.88(974) = \boxed{857 \text{ kips}}$$

$$P'_{cr_2} = 0.88(399) = \boxed{351 \text{ kips}}$$

Allowable axial for combined bending check:

$$Cc = \left(\frac{\pi^2 EA}{P_{cr}}\right)^{1/2} = \left[\frac{\pi^2(29{,}000)21.46}{351}\right]^{1/2} = 132.2$$

$$Cc = \left(\frac{2\pi^2 E}{F_y}\right)^{1/2} = \left[\frac{2\pi^2(29{,}000)}{36}\right]^{1/2} = 126.0$$

$$Cc < \left(\frac{\pi^2 EA}{P_{cr}}\right)^{1/2}$$

$$ACC = \frac{PCR}{SF} = \frac{351}{1.92} = \boxed{183 \text{ KIPS}}$$

$$ATT = 0.60F_y(A) = 0.60(36)21.46 = \boxed{464 \text{ KIPS}}$$

Allowable axial forces based on soil properties or code requirements

For this problem use an allowable compressive stress of 10 ksi, and an allowable tensile stress of 5 ksi:

$$AC = 10(21.46) = \boxed{210 \text{ kips}}$$

$$AT = 5(21.46) = \boxed{105 \text{ kips}}$$

Allowable bending moments

Bending about minor axis:

$$F_b = F_y\left[1.075 - 0.005\left(\frac{bf}{2t_f}\right)\sqrt{F_y}\right] = 0.643\ F_y$$

Bending about major axis:

$$LF = 1.8T = 1.8(6.11) = 11 \text{ FT}$$

$$LT = LU + LF = 28 + 11 = 39 \text{ FT} \qquad \text{use } 40 \text{ FT}$$

$$\frac{76bf}{\sqrt{f_y}} = \frac{76(14.6)}{\sqrt{36}} = 184.9 \text{ in.} = 15.4 \text{ FT} < 40 \text{ FT}$$

$$\sqrt{\frac{102 \times 10^3\ Cb}{F_y}} = \sqrt{\frac{102(1.00)(1,000)}{36}} = 53.2$$

$$\sqrt{\frac{510 \times 10^3\ Cb}{F_y}} = \sqrt{\frac{510(1.00)(1,000)}{36}} = 119.0$$

$$\frac{\ell}{r_T} = \frac{40(12)}{3.90} = 123 > 119$$

$$F_b = \frac{170 \times 10^3 \ Cb}{\left(\frac{\ell}{r_T}\right)^2} = \frac{170(1.00)1,000}{(123)^2} = 11.24 \text{ KSI} = 0.31 \ F_y$$

$$F_b = \frac{12 \times 10^3 \ Cb}{\frac{\ell(d)}{Af}} = \frac{12(1.00)1,000}{40(12)(1.85)} = 13.5 \text{ KSI} = 0.225 \ F_y$$

$$\text{Use } F_b \text{ (major axis)} = 0.31 \ F_y$$

$$AM1 = F_b(\text{major}) \cdot S1 = 0.31(36)107.5 = 1,200 \text{ in.-kips}$$

$$AM2 = F_b(\text{minor}) \cdot S2 = 0.643(36)35.9 = 830 \text{ in.-kips}$$

Compute design moment factors for pinned piles

Figure B19

$$m1 = 4.6, \ (H_1) = 0.19$$

$$m2 = 5.6, \ (H_2) = 0.16$$

$$KMP1 = \frac{T}{(H1)} = \frac{73.36}{0.19} = \boxed{386 \text{ in.}}$$

$$KMP2 = \frac{T}{(H2)} = \frac{59.72}{0.16} = \boxed{373 \text{ in.}}$$

Example Froblem 4

INPUT TO CPGA

Data Group								
(a)	TITLE CANTILEVER PILE GROUP - STEEL PILES							
(b)	E	11	12	A	C33	B66	LIST	
PROP	29000.	733.1	261.9	21.46	1.0	0.	1 TO 14	
(c)	PSOIL	ESOIL	LENGTH	L	LU	LIST		
SOIL	NH	0.010	L	135.	28.	1 TO 14		
(d)	FIXITY	LIST						
	PIN	1 TO 14						
(e)	PILE STIFFNESS (Based on Soil and Pile Properties - Omit)							
(f)	TENSION PILE STIFFNESS MODIFIER (Not used)							
(g)	ALLOWABLE LOADS STEEL and TIMBER PILES							
ALLOW	SHAPE	AC	AT	ACC	ATT	AM1	AM2	LIST
	H	210.	105.	183.	464.	1200.	830.	1 TO 14
(h)	DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE PILES (Not Used)							
(i)	ALLOWABLE STRESS CHECK - PRESTRESSED CONC PILES (Not Used)							
(j)	UNSUPPORTED PILE DATA							
UNSP	MATL	CM1	CM2	PCR1	PCR2	ST	LIST	
	S	.6	.6	857.	351.	N	1 TO 14	
(k)	DESIGN MOMENT FACTORS (Pinned Piles)							
PMAXMOM	KMP1	KMP2	LIST					
	386.	373.	1 TO 14					

INPUT TO CPGA CONTINUED

(l) MOMENT FACTORS FOR UNSUPPORTED PILES (Fixed Only)

KMF1U KMF2U LIST

(Not Used Since Piles are Pinned)

(m) OVERSTRESS FACTORS

OSF OSFT LIST

(Not Used, Default to 1.0)

(n) PILE BATTER

	BAT	LIST
BATTER	4.	1 TO 14

(o) ANGLE TO BATTER DIRECTION

	ANG	LIST
ANGLE	0.	4 5 6 12 13
ANGLE	90.	1 7
ANGLE	180.	2 3 9 10 11
ANGLE	270.	8 14

(p) PILE COORDINATES

	PNn	Xn	Yn	Zn
PILE	1	-15.	5.	0.
	8	-15.	-5.	0.

(q) PILE ROW GENERATION

	AXIS	NP	PN1	SP1
ROW	X	7	1	6 AT 5.0
ROW	X	7	8	6 AT 5.0

(y) LOAD CASES

LCN	PX	PY	PZ	MX	MY	MZ
1	-83.3	0.	666.7	0.	1389.	0.

(aa) OUTPUT

TOUT 1 2 3 4 5 6 7

(ee) PILE FORCE OUTPUT

	LIST
PFO	1 TO 14

Execution of Example 4A

```
**********************************
* CORPS PROGRAM * X0080     *
* MICRO VERSION * 88/11/02  *
**********************************


CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE: 89/08/10  RUN TIME: 10.16.48


   FOR PILES WITH UNSUPPORTED HEIGHT:
        A. CPGA CANNOT CALCULATE PMAXMOM FOR NH TYPE SOIL
        B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
           NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
           WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

   ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
ENTER F OR I.
F
ENTER DATA FILE NAME.
X80D4A
CANTILEVER PILE GROUP STEEL PILES
WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
N


THERE ARE  14 PILES AND
           1 LOAD CASES IN THIS RUN.

ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                                    X          Y          Z
                                  -----      -----      -----
WITH DIAGONAL COORDINATES = (    -15.00 ,    -5.00 ,      .00 )
                            (     15.00 ,     5.00 ,      .00 )


*******************************************************************************

        PILE PROPERTIES AS INPUT


     E           I1           I2           A          C33          B66
    KSI        IN**4        IN**4        IN**2
 .29000E+05  .73310E+03  .26190E+03  .21460E+02  .10000E+01  .00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

   ALL
```

****

SOIL DESCRIPTIONS AS INPUT

NH	ESOIL	LENGTH	L	LU
	K/IN**3		FT	FT
	.10000E-01	L	.13500E+03	.28000E+02

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

ALL

****

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X	Y	Z	BATTER	ANGLE	LENGTH	FIXITY
	FT	FT	FT			FT	
1	-15.00	5.00	.00	4.00	90.00	135.00	P
2	-10.00	5.00	.00	4.00	180.00	135.00	P
3	-5.00	5.00	.00	4.00	180.00	135.00	P
4	.00	5.00	.00	4.00	.00	135.00	P
5	5.00	5.00	.00	4.00	.00	135.00	P
6	10.00	5.00	.00	4.00	.00	135.00	P
7	15.00	5.00	.00	4.00	90.00	135.00	P
8	-15.00	-5.00	.00	4.00	270.00	135.00	P
9	-10.00	-5.00	.00	4.00	180.00	135.00	P
10	-5.00	-5.00	.00	4.00	180.00	135.00	P
11	.00	-5.00	.00	4.00	180.00	135.00	P
12	5.00	-5.00	.00	4.00	.00	135.00	P
13	10.00	-5.00	.00	4.00	.00	135.00	P
14	15.00	-5.00	.00	4.00	270.00	135.00	P

						1890.00	

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	-83.3	.0	666.7	.0	1389.0	.0

****

ORIGINAL PILE GROUP STIFFNESS MATRIX

.23766E+03	.18864E-05	.15781E-04	.10831E+05	-.61065E+05	-.62345E-03
.18864E-05	.10819E+03	-.39452E-04	.15815E+05	-.28686E-02	-.90920E-04
.15781E-04	-.39452E-04	.50624E+04	-.20554E-04	-.82217E-05	-.10831E+05
.10831E+05	.15815E+05	-.20554E-04	.20168E+08	-.56427E+04	-.65753E-01
-.61065E+05	-.28686E-02	-.82217E-05	-.56427E+04	.74281E+08	.31231E+00
-.62345E-03	-.90920E-04	-.10831E+05	-.65753E-01	.31231E+00	.43569E+07

14 PILES 1 LOAD CASES

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

****

PILE CAP DISPLACEMENTS

LOAD CASE	DX IN	DY IN	DZ IN	RX RAD	RY RAD	RZ RAD
1	-.3847E+00	-.3411E-01	.1324E+00	.2333E-03	-.9188E-04	.3291E-03

****

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF
1	-.1	.7	39.7	278.2	43.1	.0	.19	.50
2	.2	.3	88.1	106.5	-84.0	.0	.42	.69
3	.2	.2	90.2	94.5	-83.8	.0	.43	.69
4	-.3	-.1	16.9	-50.3	98.7	.0	.08	.25
5	-.3	-.1	18.9	-38.4	99.0	.0	.09	.25
6	-.3	-.1	21.0	-26.5	99.3	.0	.10	.26
7	-.1	.7	63.1	278.2	20.1	.0	.30	.60
8	.1	-.6	46.7	-222.0	-31.0	.0	.22	.48
9	.2	.3	74.0	106.5	-77.3	.0	.35	.59
10	.2	.2	76.1	94.5	-77.0	.0	.36	.59
11	.2	.2	78.1	82.6	-76.7	.0	.37	.59
12	-.2	-.1	12.2	-38.4	89.3	.0	.06	.21
13	-.2	-.1	14.2	-26.5	89.6	.0	.07	.21
14	.0	-.6	47.9	-222.0	-4.6	.0	.23	.45

****

PILE FORCES IN GLOBAL GEOMETRY

LOAD CASE - 1

PILE	PX K	PY K	PZ K	MX IN-K	MY IN-K	MZ IN-K
1	-.7	9.5	38.5	38.9	-235.0	58.7
2	-21.6	-.3	85.5	89.9	-75.7	22.5
3	-22.1	-.2	87.4	79.8	-75.4	20.0
4	3.8	-.1	16.4	42.5	-89.0	-10.6
5	4.3	-.1	18.4	32.4	-89.2	-8.1
6	4.8	-.1	20.4	22.3	-89.5	-5.6
7	-.7	15.2	61.2	18.1	-235.0	58.7
8	-.6	-11.4	45.2	28.0	-187.5	-46.9
9	-18.2	-.3	71.8	89.9	-69.6	22.5
10	-18.7	-.2	73.8	79.8	-69.3	20.0
11	-19.1	-.2	75.8	69.8	-69.1	17.4
12	2.7	-.1	11.9	32.4	-80.5	-8.1
13	3.2	-.1	13.9	22.3	-80.7	-5.6
14	-.6	-11.6	46.5	4.1	-187.5	-46.9

```
SHOULD THE INPUT FILE NAMED
X80D4A
BE LISTED? (Y OR N)
Y
10 CANTILEVER PILE GROUP STEEL PILES
20 PROP 29000. 733.1 261.9 21.46 1.0 0.0 1 TO 14
30 SOIL MH .010 L 135. 28. 1 TO 14
40 PIN 1 TO 14
50 ALLOW H 210. 105. 183. 464. 1200. 830. 1 TO 14
70 UNSP S 0.6 0.6 857. 351. N 1 TO 14
80 PMAXMOM 386. 373. 1 TO 14
90 BATTER 4. 1 TO 14
100 ANGLE 0. 4 5 6 12 13
110 ANGLE 90. 1 7
120 ANGLE 180. 2 3 9 10 11
130 ANGLE 270. 8 14
140 PILE 1 -15. 5. 0.
150 8 -15. -5. 0.
160 ROW X 7 1 6 AT 5.0
170 ROW X 7 8 6 AT 5.0
180 LOAD 1 -83.3 0. 666.7 0. 1389. 0.
190 TOUT 1 2 3 4 5 6 7
200 PFO 1 TO 14


ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
*
RUN CPGA AGAIN? (Y OR N)
N


NO FILES WERE GENERATED DURING THIS RUN.
Stop - Program terminated.
```

Check CPGA output - Steel H-Pile--Pile No. 3

Part I, Equation 1:

$$ALF = \frac{F3}{AC} = \frac{90.2}{210} = 0.43 \qquad \text{ok}$$

Part I, Equation 3:

$$CBF = \frac{F3}{ACC} + (MF1)\frac{|M1|}{AM1} + (MF2)\frac{|M2|}{AM2}$$

$$MF = \frac{CM}{1 - \frac{F3(SF)}{PCR}}$$

$$MF1 = \frac{0.6}{1 - \frac{90.2(1.92)}{857}} = 0.75 < 1.0, \text{ use } 1.0$$

$$MF2 = \frac{0.6}{1 - \frac{90.2(1.92)}{351}} = 1.18$$

$$CBF = \frac{90.2}{183} + \frac{1.0(94.5)}{1,200} + \frac{1.18(83.8)}{830}$$

$$CBF = 0.493 + 0.079 + 0.119 = 0.69 \qquad \text{ok}$$

Example Problem 5

20. The foundation shown in Figure B20 supports a control tower. The steel "H" piles are layed out in two (2) concentric circles. The inner circle of 12 vertical piles are 63 ft long and the outer circle of six (6) battered piles are 74 ft long. The piles are assumed to act in end bearing and pile heads are assumed pinned. The clay soil has medium strength with an E_s of 312 psi.

21. Computations and pile properties necessary to determine input items to the CPGA program are shown, followed by input, and finally output. The layout of the pile groups utilizes pile arc generation.

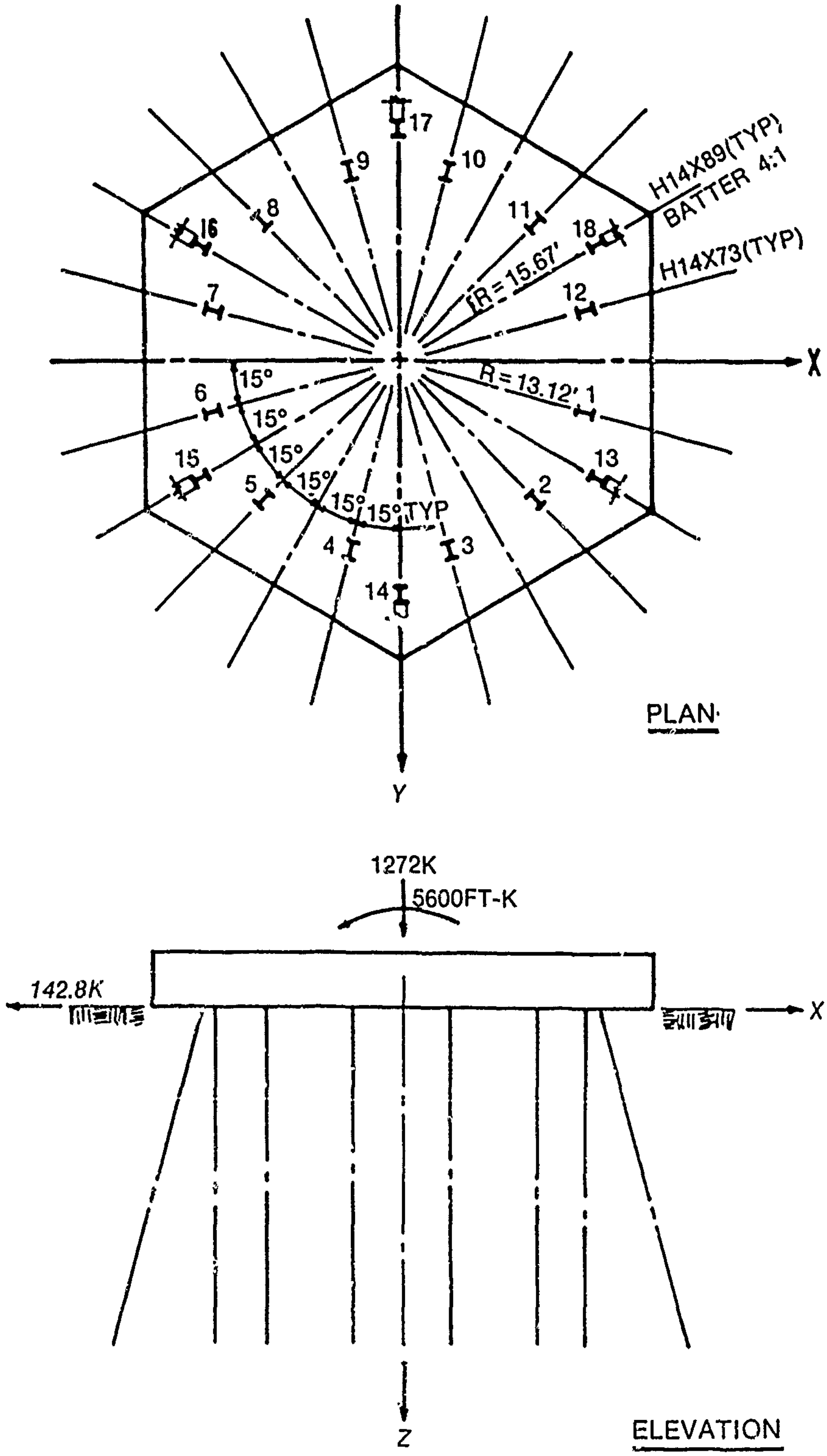


Figure B20. Pile layout for Example Problem 5

Pile Properties

HP 14 × 89

$E = 29{,}000$ ksi

$I_1 = 326$ in.^{4}

$I_2 = 904$ in.^{4}

$A = 26.1$ in.^{2}

Length = 74 ft

$S_1 = 44.3$ in.^{3}

$S_2 = 131$ in.^{3}

ES = 0.312 ksi

HP 14 × 73

$E = 29{,}000$ ksi

$I_1 = 261$ in.^{4}

$I_2 = 724$ in.^{4}

$A = 21.4$ in.^{2}

Length = 62 ft

$S_1 = 35.6$ in.^{3}

$S_2 = 107$ in.^{3}

ES = 0.312 ksi

Fixity = pinned

C33 = 1.0

B66 = 0.0

Allowables

HP 14 × 89

AC = 150 kips

AT = 75 kips

ACC = 26.1 × 17.0 = 443.7 kips

ATT = 26.1 × 20.0 = 522 kips

AM1 = 44.3 × 22.0 = 975 kips-in.

AM2 = 131 × 22.0 = 2,882 kips-in.

HP 14 × 73

AC = 100 kips

AT = 50 kips

ACC = 21.4 × 17.0 = 363.8 kips

ATT = 21.4 × 20.0 = 428 kips

AM1 = 35.6 × 22.0 = 770 kips-in.

AM2 = 107 × 22.0 = 2,354 kips-in.

Reference: Table A-2, "Basic Pile Group Behavior," Technical Report K-83-1; Table A-2, Draft Pile EM.

Example Problem 5

INPUT FOR CPGA

Data Group	Line No.	
(a)		TITLE.
	100	EXAMPLE PROBLEM 5 - CONTROL TOWER
(b)		PILE PROPERTIES.

```
         E     I1  I2   A    C33 B66    LIST
110 PROP 29000 326 904 26.1   1   0   13 TO 18
120 PROP 29000 261 724 21.4   1   0    1 TO 12
```

(c) SOIL DESCRIPTION.

```
         PSOIL  ESOIL  LENGTH  LZ  UNS    LIST
130 SOIL  ES    .312     L     74   0   13 TO 18
140 SOIL  ES    .312     L     63   0    1 TO 12
```

(d) FIXITY.

```
    FIXITY  LIST
150 PIN     ALL
```

(e) PILE STIFFNESS.
(BASED ON SOIL AND PILE STRUCTURES)
OMIT (NOT APPLICABLE)

(f) TENSION PILE STIFFNESS MODIFIER.
OMIT (NOT APPLICABLE)

(g) ALLOWABLE LOADS (STEEL AND TIMBER PILES).

```
          SHAPE  AC   AT   ACC   ATT  AM1  AM2    LIST
160 ALLOW   H   150   75  443.7  522  975  2882 13 TO 18
170 ALLOW   H   100   50  363.8  428  770  2354  1 TO 12
```

(h) DESIGN LOAD STRENGTHS - PRESTRESSED CONCRETE OR REINFORCED CONCRETE PILES.
OMIT (NOT APPLICABLE)

(i) ALLOWABLE - STRESS CHECK - PRESTRESSED CONCRETE PILES.
OMIT (NOT APPLICABLE)

(j) UNSUPPORTED PILE DATA.
OMIT (NOT APPLICABLE)

(k) DESIGN MOMENT FACTORS FOR PINNED PILE.
NOT INPUTTED - DEFAULT VALUES USED.

(l) MOMENT FACTORS FOR FIXED UNSUPPORTED PILES.
OMIT (NOT APPLICABLE)

(m) OVERSTRESS FACTORS.
OMIT (DEFAULT TO 1.0)

```
(n)          PILE BATTER.
                        BAT    LIST
       180   BATTER      4    13 TO 18

(o)          ANGLE TO BATTER DIRECTION.
                        ANG   LIST
       190   ANGLE       15     1
       200   ANGLE       45     2
       210   ANGLE       75     3
       220   ANGLE      105     4
       230   ANGLE      135     5
       240   ANGLE      165     6
       250   ANGLE      195     7
       260   ANGLE      225     8
       270   ANGLE      255     9
       280   ANGLE      285    10
       290   ANGLE      315    11
       300   ANGLE      345    12
       310   ANGLE       30    13
       320   ANGLE       90    14
       330   ANGLE      150    15
       340   ANGLE      210    16
       350   ANGLE      270    17
       360   ANGLE      330    18

(p)          PILE COORDINATES.
                   PN1    X1     Y1    Z1  PN2     X2      Y2    Z2
       370   PILE   1   12.67   3.39   0   13    13.57    7.84    0

(q)          PILE ROW GENERATION.
             OMIT (NOT APPLICABLE)

(r)          REPEAT ROWS OF PILES.
             OMIT (NOT APPLICABLE)

(s)          PILE ARC GENERATION.
                  CENTER   RAD    ANG   PN1   NP      SP1
       380   ARC  0 0 0   13.12   15     1    12   11 AT 30
       390   ARC  0 0 0   15.67   30    13     6    5 AT 60

(t)          REPEAT ARCS OF PILES.
             OMIT (NOT APPLICABLE)

(u)          DUPLICATE PILE ZONES.
             OMIT (NOT APPLICABLE)

(v)          ROTATE PILE ZONES.
             OMIT (NOT APPLICABLE)

(w)          SLOPE BASE DESCRIPTION.
             OMIT (NOT APPLICABLE)

(x)          PILE DELETION.
             OMIT (NOT APPLICABLE)
```

```
(y)            LOAD CASES.
                      LCN     PX     PY    PZ    MX    MY    MZ
        400    LOAD    1   -142.8    0    1272    0   5600    0

(z)            SPECIFIED PILE CAP DISPLACEMENTS.
               OMIT (NOT APPLICABLE)

(aa)           OUTPUT AT TERMINAL.
                      LIST
        410    TOUT  1  2  5

(bb)           OUTPUT TO FILE.
               OMIT (NOT APPLICABLE)

(cc)           PILE STIFFNESS OUTPUT.
               OMIT INPUT - (DEFAULT TO PILE #1)

(dd)           PILE CAP DISPLACEMENT OUTPUT.
               OMIT INPUT - (DEFAULT TO ORIGIN)

(ee)           PILE FORCE OUTPUT.
                     LIST
        420    PFO    ALL

(ff)           PILE COORDINATES OUTPUT.
               OMIT (DEFAULT TO PRINT ALL PILE LOCATIONS
                     AND BATTERS)

(gg)           FPL.
               OMIT (NOT APPLICABLE)
```

Listing of Input Data File for Problem 5

```
1000 EXAMPLE 5 - CONTROL TOWER
1010 PROP 29000 326 904 26.1 1 0 13 TO 18
1020 PROP 29000 261 724 21.4 1 0 1 TO 12
1050 SOIL ES .312 L 74 0 13 TO 18
1060 SOIL ES .312 L 63 0 1 TO 12
1070 PIN ALL
1080 ALLOW H 150 75 443.7 522 975 2882 13 TO 18
1090 ALLOW H 100 50 363.8 428 770 2354 1 TO 12
1100 BATTER 4 13 TO 18
1130 ANGLE 15 1
1140 ANGLE 45 2
1150 ANGLE 75 3
1160 ANGLE 105 4
1170 ANGLE 135 5
1180 ANGLE 165 6
1190 ANGLE 195 7
1200 ANGLE 225 8
1210 ANGLE 255 9
1220 ANGLE 285 10
1230 ANGLE 315 11
1240 ANGLE 345 12
1250 ANGLE 30 13
1260 ANGLE 90 14
1270 ANGLE 150 15
1280 ANGLE 210 16
1290 ANGLE 270 17
1300 ANGLE 330 18
1310 PILE 1 12.67 3.39 0 13 13.57 7.84 0
1320 ARC 0 0 0 13.12 15 1 12 11 AT 30
1330 ARC 0 0 0 15.67 30 13 6 5 AT 60
1335 LOAD 1 -142.8 0 1272 0 5600 0
1340 TOUT 1 2 5
1350 PFO ALL
```

Listing of Output File for Problem 5

```
********************************
*  CORPS PROGRAM *  X0080      *
*    CDC VERSION * 86/09/02-A  *
********************************

CPGA - CASE PILE GROUP ANALYSIS PROGRAM
RUN DATE  88/04/07   RUN TIME  14.47.57


     FOR PILES WITH UNSUPPORTED HEIGHT:
          A. CPGA CANNOT CALCULATE PMAXMOM FOR NH TYPE SOIL
          B. THE ALLOWABLE STRESS CHECKS, ASC AND AST, ARE
             NOT FULLY DEVELOPED FOR UNSUPPORTED PILES.
             WORK IS IN PROGRESS TO COMPLETE THIS ASPECT OF CPGA.

     ELASTIC CENTER LOCATION IS NOT COMPUTED FOR 3-DIMENSIONAL PROBLEMS.


 DO YOU WANT TO USE AN EXISTING FILE OR INTERACTIVE INPUT?
 ENTER F OR I.
? F
 ENTER DATA FILE NAME.
? X80D5
 EXAMPLE 5 - CONTROL TOWER

 WILL OUTPUT BE PLOTTED BY CPGG? (Y OR N)
? N


 THERE ARE  18 PILES AND
             1 LOAD CASES IN THIS RUN.

 ALL PILE COORDINATES ARE CONTAINED WITHIN A BOX
                                  X          Y          Z
                                -----      -----      -----
 WITH DIAGONAL COORDINATES = (   -13.57 ,   -15.67 ,      .00 )
                             (    13.57 ,    15.67 ,      .00 )
```

****

PILE PROPERTIES AS INPUT

E	I1	I2	A	C33	B66
KSI	IN**4	IN**4	IN**2		
.29000E+05	.32600E+03	.90400E+03	.26100E+02	.10000E+01	.00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

13 14 15 16 17 18

E	I1	I2	A	C33	B66
KSI	IN**4	IN**4	IN**2		
.29000E+05	.26100E+03	.72400E+03	.21400E+02	.10000E+01	.00000E+00

THESE PILE PROPERTIES APPLY TO THE FOLLOWING PILES -

1 2 3 4 5 6 7 8 9 10 11 12

****

SOIL DESCRIPTIONS AS INPUT

ES	ESOIL	LENGTH	L	LU
	K/IN**2		FT	FT
	.31200E+00	L	.74000E+02	.00000E+00

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

13 14 15 16 17 18

ES	ESOIL	LENGTH	L	LU
	K/IN**2		FT	FT
	.31200E+00	L	.63000E+02	.00000E+00

THIS SOIL DESCRIPTION APPLIES TO THE FOLLOWING PILES -

1 2 3 4 5 6 7 8 9 10 11 12

****

PILE GEOMETRY AS INPUT AND/OR GENERATED

NUM	X FT	Y FT	Z FT	BATTER	ANGLE	LENGTH FT	FIXITY
1	12.67	3.40	.00	V	15.00	63.00	P
2	9.28	9.28	.00	V	45.00	63.00	P
3	3.40	12.67	.00	V	75.00	63.00	P
4	-3.40	12.67	.00	V	105.00	63.00	P
5	-9.28	9.28	.00	V	135.00	63.00	P
6	-12.67	3.40	.00	V	165.00	63.00	P
7	-12.67	-3.40	.00	V	195.00	63.00	P
8	-9.28	-9.28	.00	V	225.00	63.00	P
9	-3.40	-12.67	.00	V	255.00	63.00	P
10	3.40	-12.67	.00	V	285.00	63.00	P
11	9.28	-9.28	.00	V	315.00	63.00	P
12	12.67	-3.40	.00	V	345.00	63.00	P
13	13.57	7.83	.00	4.00	30.00	74.00	P
14	.00	15.67	.00	4.00	90.00	74.00	P
15	-13.57	7.84	.00	4.00	150.00	74.00	P
16	-13.57	-7.83	.00	4.00	210.00	74.00	P
17	.00	-15.67	.00	4.00	270.00	74.00	P
18	13.57	-7.84	.00	4.00	330.00	74.00	P

						1200.00	

****

APPLIED LOADS

LOAD CASE	PX K	PY K	PZ K	MX FT-K	MY FT-K	MZ FT-K
1	-142.8	.0	1272.0	.0	5600.0	.0

18 PILES 1 LOAD CASES

LOAD CASE 1. NUMBER OF FAILURES = 0. NUMBER OF PILES IN TENSION = 0.

****

PILE FORCES IN LOCAL GEOMETRY

M1 & M2 NOT AT PILE HEAD FOR PINNED PILES
* INDICATES PILE FAILURE
# INDICATES CBF BASED ON MOMENTS DUE TO
(F3*EMIN) FOR CONCRETE PILES
B INDICATES BUCKLING CONTROLS

LOAD CASE - 1

PILE	F1 K	F2 K	F3 K	M1 IN-K	M2 IN-K	M3 IN-K	ALF	CBF
1	-5.0	1.0	47.9	33.2	206.2	.0	.48	.26
2	-3.7	2.8	54.1	90.6	150.9	.0	.54	.33
3	-1.3	3.9	64.9	123.8	55.3	.0	.65	.36
4	1.3	3.9	77.4	123.8	-55.3	.0	.77	.40
5	3.7	2.8	88.2	90.6	-150.9	.0	.88	.42
6	5.0	1.0	94.4	33.2	-206.2	.0	.94	.39
7	5.0	-1.0	94.4	-33.2	-206.2	.0	.94	.39
8	3.7	-2.8	88.2	-90.6	-150.9	.0	.88	.42
9	1.3	-3.9	77.4	-123.8	-55.3	.0	.77	.40
10	-1.3	-3.9	64.9	-123.8	55.3	.0	.65	.36
11	-3.7	-2.8	54.1	-90.6	150.9	.0	.54	.33
12	-5.0	-1.0	47.9	-33.2	206.2	.0	.48	.26
13	-4.9	2.1	.2	71.6	213.0	.0	.00	.15
14	-.4	4.2	71.7	143.2	19.4	.0	.48	.32
15	4.0	2.1	143.2	71.6	-174.3	.0	.95	.46
16	4.0	-2.1	143.2	-71.6	-174.3	.0	.95	.46
17	-.4	-4.2	71.7	-143.2	19.4	.0	.48	.32
18	-4.9	-2.1	.2	-71.6	213.0	.0	.00	.15

SHOULD THE INPUT FILE NAMED 'X80D5 ' BE LISTED? (Y OR N)
? N

ENTER CHANGE TO INPUT FILE OR * WHEN DONE.
? *
RUN CPGA AGAIN? (Y OR N)
? N

NO FILES WERE GENERATED DURING THIS RUN.
EXIT.

APPENDIX C: NOTATION

FORTRAN SYMBOL	MATHEMATICAL SYMBOL	
A	A, A_c	Cross-sectional area of pile
	As	Area of reinforcing steel
AC	AC	Allowable pile compression load
ACC	ACC	Allowable axial compression load for the combined bending and axial load check.
AM1,AM2	AM1,AM2	Allowable moment about local 1 and 2 pile axes for combined bending and axial load check.
ANG	ANG	Orientation angle of pile
ASC	ASC	Maximum compressive stress or minimum tensile stress for prestressed concrete piles
AST	AST	Maximum tensile stress or minimum compressive stress for prestressed concrete piles
AT	AT	Allowable pile tension load
ATT	ATT	Allowable axial tension load for combined bending and axial load check
BAT	BAT	Slope ratio of pile batter (vertical/horizontal)
BIJ	b_{ij}	Elements of the pile stiffness matrix
	[B]	Pile stiffness matrix
CO	C_o	Pile fixity constant
C33	C_{33}	Axial stiffness modifier which accounts for the interaction between the soil and the embedded portion of the pile
CM1,CM2	CM1,CM2	Moment diagram shape factor for unsupported piles about the local 1 and 2 axes

FORTRAN SYMBOL	MATHEMATICAL SYMBOL	
DX,DY,DZ	D_x, D_y, D_z	Magnitude of translation along the global X, Y, and Z axes
E	E	Modulus of elasticity of pile material
ES	E_s	Stiffness of horizontal subgrade reaction
EZ	E_z	Stiffness of vertical subgrade reaction
F1,F2,F3	F_1, F_2, F_3	Forces along the local pile axes 1, 2, and 3
FA	FA	Allowable compressive stress in concrete for prestressed concrete piles
	f'_c	Specified concrete compressive strength
FPC	fpc	Concrete str [illegible] due to final prestress force
FT	FT	Allowable tensile stress in concrete for prestressed concrete piles
FY	Fy	Specified yield strength of reinforcement or prestressing steel
	G	Shear modulus of the pile
HIJ	H_{ij}	Elements of the pile group flexibility matrix
	[H]	Pile group flexibility matrix
I1,I2	I_1, I_2	Moment of inertia of pile about local 1 and 2 axes
IPC	IPC	Concrete stress due to initial prestress force
J	J	Polar moment of inertia of the pile
	[K]	Assembled stiffness matrix for entire pile
K	K	Moment capacity reduction factor (para 24 i and 38)
KMF1U	KMF1U	Moment factor for computation of maximum M1 in fixed head pile

FORTRAN SYMBOL	MATHEMATICAL SYMBOL	
KMF2U	KMF2U	Moment factor for computation of maximum M2 in fixed head pile
KMP1	KMP1	Moment factor for computation of maximum M1 in pinned head pile
KMP2	KMP2	Moment factor for computation of maximum M2 in pinned head pile
L	L	Length of entire pile
LE	L_e	Embedded length of pile
LF	L_f	Depth to fixity of pile
LT	L_t	Free standing length (L_u) plus depth to fixity (L_f) of pile
LU	L_u	Unsupported length of pile above ground line
M1,M2,M3	M_1,M_2,M_3	Magnitude of moments about local 1, 2, and 3 pile axes
M1U,M2U	M1U,M2U	Moment factors for fixed unsupported piles about local 1 and 2 axes
MB	MB	Design moment strength of the pile at simultaneous, assumed ultimate strain of concrete and yielding of tension reinforcement balanced condition
MF1,MF2	MF1,MF2	Moment magnification factors about local 1 and 2 pile axes
MX,MY,MZ	M_x,M_y,M_z	Applied moments along the X, Y, and Z axes
NH	n_h	Constant of horizontal subgrade reaction or the change in the E_s with depth
OSF	OSF	Overstress factor
OSFT	OSFT	Overstress factor for pile tension load
PB	PB	Axial design load strength of the pile in simultaneous, assumed, ultimate strain of concrete and yielding of tension reinforcement, balanced conditions.

FORTRAN SYMBOL	MATHEMATICAL SYMBOL	
PCR1,PCR2	PCR1,PCR2	Critical loads for buckling about the local 1 and 2 axes for unsupported piles
PO	PO	Axial design load strength of the concrete pile in compression under pure axial load
PT	PT	Axial design load strength of the concrete pile in tension under pure axial load
PX,PY,PZ	P_x, P_y, P_z	Applied forces along the X, Y, and Z axes
	$\{q\}$	Vector of local pile forces and moments about the local 1, 2, and 3 axes
R1,R2	R_1, R_2	Characteristic length about the local 1 and 2 axes for uniform subgrade modulus
RX,RY,RZ	R_x, R_y, R_z	Magnitude of rotation about the global X, Y, and Z axes
S1,S2	S_1, S_2	Section modulus of the pile about the local 1 and 2 axes
	SF	Factor of safety
T1,T2	T_1, T_2	Characteristic length coefficient about the local 1 and 2 axes for a linear subgrade modulus
	$\{u\} = \begin{Bmatrix} u \\ v \\ w \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{Bmatrix}$	Local displacement vector at the head of the pile

FORTRAN SYMBOL	MATHEMATICAL SYMBOL	
	$\{U\} = \begin{Bmatrix} Dx \\ Dy \\ Dz \\ Rx \\ Ry \\ Rz \end{Bmatrix}$	Displacement vector of pile cap in global coordinates
X,Y,Z	X,Y,Z	Global coordinates
XN,YN,ZN	X_n, Y_n, Z_n	X, Y, and Z coordinates of pile n
	1,2,3	Local coordinates of a pile
	x,y,z	Local coordinates of a pile

WATERWAYS EXPERIMENT STATION REPORTS PUBLISHED UNDER THE COMPUTER-AIDED STRUCTURAL ENGINEERING (CASE) PROJECT

	Title	Date
Technical Report K-78-1	List of Computer Programs for Computer-Aided Structural Engineering	Feb 1978
Instruction Report O-79-2	User's Guide: Computer Program with Interactive Graphics for Analysis of Plane Frame Structures (CFRAME)	Mar 1979
Technical Report K-80-1	Survey of Bridge-Oriented Design Software	Jan 1980
Technical Report K-80-2	Evaluation of Computer Programs for the Design/Analysis of Highway and Railway Bridges	Jan 1980
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	Title	Date
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